Universidade de Aveiro
2012

Departamento de Engenharia Electrónica,
Telecomunicações e Informática

Pedro Miguel Naia Neves

Acesso Banda Larga Sem Fios em Ambientes Heterogéneos de Próxima Geração

Universidade de Aveiro
2012

Departamento de Engenharia Electrónica, Telecomunicações e Informática

Pedro Miguel Naia Neves

Acesso Banda Larga Sem Fios em Ambientes Heterogéneos de Próxima Geração

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Doutor em Engenharia Informática, realizada sob a orientação científica da Professora Doutora Susana Sargento, Professora Auxiliar do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro, e do Professor Francisco Fontes, Professor Auxiliar Convidado do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro.

Apoio financeiro da FCT e do FSE no âmbito do III Quadro Comunitário de Apoio.

Para as três flores da minha vida – Ana Luísa, Eva e Rita.

o júri

presidente

Prof.ª Doutora Celeste de Oliveira Alves Coelho
professora catedrática do Departamento de Ambiente e Ordenamento da Universidade de Aveiro

Prof. Doutor Fernando José da Silva Velez
professor auxiliar do Departamento de Engenharia Electromecânica da Universidade da Beira Interior

Prof.ª Doutora Marília Pascoal Curado
professora auxiliar da Faculdade de Ciências e Tecnologia da Universidade de Coimbra

Prof. Doutor André Ventura da Cruz Marnoto Zúquete
professor auxiliar do Departamento de Engenharia Electrónica, Telecomunicações e Informática da Universidade de Aveiro

Prof.ª Doutora Susana Isabel Barreto de Miranda Sargento
professora auxiliar do Departamento de Engenharia Electrónica, Telecomunicações e Informática da Universidade de Aveiro (orientador)

Prof. Doutor Francisco Manuel Marques Fontes
professor auxiliar convidado do Departamento de Engenharia Electrónica, Telecomunicações e Informática da Universidade de Aveiro (coorientador)

agradecimentos

Cabe-me expressar as minhas primeiras palavras de agradecimento, aos meus orientadores, a Professora Susana Sargento e o Professor Francisco Fontes, por estarem sempre disponíveis para esclarecer as dúvidas existentes e partilhar os seus conhecimentos. Revelou-se importante o espírito critico demonstrado por ambos na procura das melhores soluções para os problemas encontrados nesta Tese.

À PT Inovação por me ter dado a oportunidade de desenvolver esta Tese num ambiente empresarial, que permitiu compatibilizar os desafios da minha atividade profissional com as atividades científicas aqui apresentadas. Neste contexto, um especial agradecimento à Eng.ª Telma Mota e ao Eng.º Luís Miguel Silva pelo apoio e incentivo que sempre me transmitiram. Estendo este agradecimento a todos os colegas da PT Inovação, e em particular do IEX1 (Inovação Exploratória), que, direta ou indiretamente, colaboraram no desenvolvimento desta Tese.

Ao Instituto de Telecomunicações de Aveiro por me ter oferecido todas as condições e apoio necessários. Destaco os colegas do grupo NAP (*Network Architectures and Protocols*), bem como os alunos de mestrado Telmo Pereira, Ricardo Matos, Márcio Melo, João Soares, Nuno Pássaro, Nelson Capela, Tiago Cardoso, Ricardo Silva e André Barbosa pelas discussões científicas e pelos resultados experimentais que me ajudaram a obter.

Ao Dr. Kostas Pentikousis pela partilha de conhecimentos e experiência, e também pela criatividade, motivação e inspiração que sempre me transmitiu. Aos colegas Bruno Sousa e Luís Cordeiro, alunos de doutoramento da Faculdade de Ciências e Tecnologia da Universidade de Coimbra, pelas importantes discussões e resultados partilhados durante a elaboração desta Tese.

À Fundação para a Ciência e Tecnologia pela bolsa de doutoramento que me foi atribuída.

À minha esposa, Ana Luísa, às minhas filhas, Eva e Rita, e a toda a minha família pelo incansável apoio, paciência e motivação que me deram durante o desenvolvimento desta Tese.

palavras-chave

4G, redes de acesso sem-fios heterogéneas, WiMAX, UMTS/HSPA, LTE, Wi-Fi, 802.21, mobilidade transparente, QoS, contexto.

resumo

O acesso ubíquo à Internet é um dos principais desafios para os operadores de telecomunicações na próxima década. O número de utilizadores da Internet está a crescer exponencialmente e o paradigma de acesso "*always connected, anytime, anywhere*" é um requisito fundamental para as redes móveis de próxima geração. A tecnologia WiMAX, juntamente com o LTE, foi recentemente reconhecida pelo ITU como uma das tecnologias de acesso compatíveis com os requisitos do 4G. Ainda assim, esta tecnologia de acesso não está completamente preparada para ambientes de próxima geração, principalmente devido à falta de mecanismos de *cross-layer* para integração de QoS e mobilidade. Adicionalmente, para além das tecnologias WiMAX e LTE, as tecnologias de acesso rádio UMTS/HSPA e Wi-Fi continuarão a ter um impacto significativo nas comunicações móveis durante os próximos anos. Deste modo, é fundamental garantir a coexistência das várias tecnologias de acesso rádio em termos de QoS e mobilidade, permitindo assim a entrega de serviços multimédia de tempo real em redes móveis.

Para garantir a entrega de serviços multimédia a utilizadores WiMAX, esta Tese propõe um gestor *cross-layer* WiMAX integrado com uma arquitectura de QoS fim-a-fim. A arquitectura apresentada permite o controlo de QoS e a comunicação bidireccional entre o sistema WiMAX e as entidades das camadas superiores. Para além disso, o gestor de *cross-layer* proposto é estendido com eventos e comandos genéricos e independentes da tecnologia para optimizar os procedimentos de mobilidade em ambientes WiMAX. Foram realizados testes para avaliar o desempenho dos procedimentos de QoS e mobilidade da arquitectura WiMAX definida, demonstrando que esta é perfeitamente capaz de entregar serviços de tempo real sem introduzir custos excessivos na rede.

No seguimento das extensões de QoS e mobilidade apresentadas para a tecnologia WiMAX, o âmbito desta Tese foi alargado para ambientes de acesso sem-fios heterogéneos. Neste sentido, é proposta uma arquitectura de mobilidade transparente com suporte de QoS para redes de acesso multi-tecnologia. A arquitectura apresentada integra uma versão estendida do IEEE 802.21 com suporte de QoS, bem como um gestor de mobilidade avançado integrado com os protocolos de gestão de mobilidade do nível IP. Finalmente, para completar o trabalho desenvolvido no âmbito desta Tese, é proposta uma extensão aos procedimentos de decisão de mobilidade em ambientes heterogéneos para incorporar a informação de contexto da rede e do terminal. Para validar e avaliar as optimizações propostas, foram desenvolvidos testes de desempenho num demonstrador inter-tecnologia, composta pelas redes de acesso WiMAX, Wi-Fi e UMTS/HSPA.

keywords

4G, heterogeneous wireless access networks, WiMAX, UMTS/HSPA, LTE, Wi-Fi, 802.21, seamless mobility, QoS, context.

abstract

Ubiquitous Internet access is one of the main challenges for the telecommunications industry in the next decade. The number of users accessing the Internet is growing exponentially and the network access paradigm of “always connected, anytime, anywhere” is a central requirement for the so-called Next Generation Mobile Networks (NGMN). WiMAX, together with LTE, was recently recognized by ITU as one of the compliant access technologies for 4G. Nevertheless, WiMAX is not yet fully prepared for next generation environments, mainly due to the lack of QoS and mobility cross-layer procedures to support real-time multimedia services delivery. Furthermore, besides the 4G compliant WiMAX and LTE radio access technologies, UMTS/HSPA and Wi-Fi will also have a significant impact in the mobile communications during the next years. Therefore, it is fundamental to ensure the coexistence of multiple radio access technologies in what QoS and mobility procedures are concerned, thereby allowing the delivery of real-time services in mobile networks.

In order to provide the WiMAX mobile users with the demanded multimedia services, it is proposed in this Thesis a WiMAX cross-layer manager integrated in an end-to-end all-IP QoS enabled architecture. The presented framework enables the QoS control and bidirectional communication between WiMAX and the upper layer network entities. Furthermore, the proposed cross-layer framework is extended with media independent events and commands to optimize the mobility procedures in WiMAX environments. Tests were made to evaluate the QoS and mobility performance of the defined architecture, demonstrating that it is perfectly capable of handling and supporting real time services without introducing an excessive cost in the network.

Following the QoS and mobility extensions provided for WiMAX, the scope of this Thesis is broaden and a seamless mobility architecture with QoS support in heterogeneous wireless access environments is proposed. The presented architecture integrates an extended version of the IEEE 802.21 framework with QoS support, as well as an advanced mobility manager integrated with the IP level mobility management protocols. Finally, to complete the work within the framework of this Thesis, it is proposed an extension to the handover decision-making processes in heterogeneous access environments through the integration of context information from both the network entities and the end-user. Performance tests were developed in a real testbed to validate the proposed optimizations in an inter-technology handover scenario involving WiMAX, Wi-Fi and UMTS/HSPA.

Table of Contents

List of Figures

List of Tables

Acronyms

3GPP	3rd Generation Partnership Project
AAA	Authentication, Authorization, Accounting
AAR	Authorize Authenticate Request
ABC	Always Best Connected
AC	Admission Control
ACIS	Access network Context-aware Information Server
ACM	Admission Control Manager
AF	Application Function
aGW	access Gateway
AIFS	Arbitration Inter Frame Space
AMI	Admin Management Interface
AN	Access Network
ANDSF	Access Network Discovery and Selection Function
AN-GW	Access Network Gateway
AP	Access Point
API	Application Programming Interface
APP	Application
AS	Application Server
ASN	Access Service Network
ASN-GW	Access Service Network Gateway
AVC	Advanced Video Coding
AVP	Attribute Value Pair
BE	Best Effort
BPSK	Binary Phase Shift Keying
BS	Base Station
BSS	Basic Service Set
BTS	Base Transceiver Station
BWA	Broadband Wireless Access
CAN	Candidate Access Network
CBR	Constant Bit Rate
CCK	Complementary Code Keying
CCIS	Core network Context-aware Information Server
CDMA	Code Division Multiple Access
CID	Connection Identifier
CINR	Carrier to Interference and Noise Ratio
CIP	Context Information Providers
CIPC	Context Information and Policies Consumer
CIPP	Context Information and Policies Provider
CIR	Context Information Repository
CIS	Context-aware Information Server
CISUA	Context-aware Information Server Update Algorithm
CLI	Command Line Interface
CM	Carvalho Mountain
CN	Core Network
CNode	Correspondent Node
COTS	Commercial Off The Shelf
CPU	Central Processing Unit
CPS	Common Part Sublayer
CS	Convergence Sublayer
CSD	Circuit Switched Domain

C-SAP	Control Service Access Point
CSC	Connectivity Service Controller
CSMA/CA	Carrier Sense Multiple Access / Collision Avoidance
C-HO-IND	Control-Handover-Indication
C-HO-REQ/RSP	Control-Handover-Request/Response
C-SFM-REQ/RSP	Control-Service Flow Manager-Request/Response
CRO	Critical Resources Occupancy Variation
C-RRM-REQ/RSP	Control-Radio Resource Manager-Request/Response
CSM	Convergence Sublayer Manager
CSN	Connectivity Service Network
DAIDALOS	Designing Advanced network Interfaces for the Delivery and Administration of Location independent, Optimized personal Services
DCD	Downlink Channel Descriptor
DCF	Distributed Coordination Function
DHCP	Dynamic Host Configuration Protocol
DiffServ	Differentiated Services
DL-MAP	Downlink Map
DNCI	Dynamic Network Context Information
DNS	Domain Name System
DS	Distributed System
DSA-REQ/RSP	Dynamic Service Addition-Request/Response
DSC-REQ/RSP	Dynamic Service Change-Request/Response
DSD-REQ/RSP	Dynamic Service Deletion-Request/Response
DSL	Digital Subscriber Line
DSLAM	Digital Subscriber Line Access Multiplexer
DSMIP	Dual Stack Mobile IP
DTCI	Dynamic Terminal Context Information
DVB	Digital Video Broadcast
EB	Exabytes
EDCA	Enhanced Distributed Channel Access
EIS	Enhanced Information Server
EMIHF	Enhanced Media Independent Handover Framework
eNB	enhanced Node B
EPC	Evolved Packet Core
ePDG	evolved Packet Data Gateway
EPS	Evolved Packet System
ertPS	extended real-time Polling Service
ESS	Extended Service Set
EthCS	Ethernet Convergence Sublayer
ETSI	European Telecommunications Standards Institute
E-UTRAN	Evolved Universal Mobile Telecommunications System Terrestrial Radio Access Network
FA	Foreign Agent
FBSS	Fast Base Station Switching
FEC	Forward Error Correction
FDD	Frequency Division Multiplex
FMIP	Fast Mobile IP
FRO	Flexible Resources Occupancy
FTP	File Transfer Protocol
GA	Generic Adapter
GANSI	General and Access Network Specific Information
GGSN	Gateway GPRS Support Node
GIS	Geographical Information System
GIST	General Internet Signaling Transport
GPRS	General Packet Radio Service

GMSC	Gateway MSC
GSM	Global System for Mobile Telecommunications
GTP	GPRS Tunneling Protocol
GW	Gateway
HA	Home Agent
HC	Hybrid Coordinator
HCCA	HCF Controlled Channel Access
HCF	Hybrid Coordination Function
HDM	Handover Decision Manager
HHO	Hard Handover
HO	Handover
HO-REQ/RSP/CNF	Handover-Request/Response/Confirm
HLR	Home Location Register
HRM	Handover Resources Manager
HSPA	High Speed Packet Access
HSDPA	High Speed Downlink Packet Access
HSUPA	High Speed Uplink Packet Access
HURRICANE	Handover for Ubiquitous and optimal bRoadband connectIvity among CooperAtive Network Environments
IAPP	Inter Access Point Protocol
IE	Information Element
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IMS	IP Multimedia Subsystem
IMT	International Mobile Telecommunications
IntServ	Integrated Services
IP	Internet Protocol
IPv4CS	Internet Protocol v4 Convergence Sublayer
IPv6CS	Internet Protocol v6 Convergence Sublayer
IPTV	Internet Protocol Television
IS	Information Server
ISF	Initial Service Flow
ITU	International Telecommunications Union
L3QoS	Layer 3 Quality of Service
LAN	Local Area Network
LLC	Link Layer Controller
LM	Lousã Mountain
LMA	Local Mobility Anchor
LOS	Line Of Sight
LQM	Link Quality Manager
LTE	Long Term Evolution
M2M	Machine to Machine
MAC	Medium Access Control
MADM	Multiple Attribute Decision Making
MAG	Mobile Access Gateway
MAN	Metropolitan Area Network
MAA	Multimedia Authorization Answer
MAR	Multimedia Authorization Request
MCSM	Media independent handover Command Service Manager
MDHO	Macro Diversity Handover
MESM	Media independent handover Event Service Manager
MGW	Media Gateway
MIB	Management Information Base
MICS	Media Independent Command Service
MIES	Media Independent Event Service

MIH	Media Independent Handover
MIH_NET_SAP	Media Independent Handover Network Service Access Point
MIHF	Media Independent Handover Function
MIHO	Mobile Initiated Handover
MIHS	Media Independent Handover management Service
MIHU	Media Independent Handover User
MIIS	Media Independent Information Service
MIMO	Multiple Input Multiple Output
MIMS	Media Independent Management Service
MIP	Mobile IP
MISM	Media independent handover Information Service Manager
MLME	MAC Sublayer Management Entity
MM	Mobility Manager
MME	Mobility Management Entity
MMR	Multi-hop Mobile Relay
MMS	Mobility Management Service
MN	Mobile Node
MOB_BSHO-REQ/RSP	Mobility-Base Station Handover-Request/Response
MOB_HO-IND	Mobility-Handover-Indication
MOB_MSHO-REQ/RSP	Mobility-Mobile Station Handover-Request/Response
MOB_SCN-REQ/RSP	Mobility-Scanning-Request/Response
MP2	Moving Picture Experts Group Audio-Layer II
MPEG	Moving Picture Experts Group
MRI	Message Routing Information
M-SAP	Management Service Access Point
MTU	Maximum Transmission Unit
MSC	Mobile Switching Centre
MSGCF	MAC State ConverGence Function
NAS	Network Access Stratum
NB	Node B
NCMS	Network Control and Management System
NDM	Network Discovery Manager
NGMN	Next Generation Mobile Networks
NGN	Next Generation Network
NIHO	Network Initiated Handover
NLOS	Non Line Of Sight
NMM	Network Mobility Manager
NMS	Network Management System
NRM	Network Reference Model
nrtPS	non real-time Polling Service
NS-2	Network Simulator 2
NSIS	Next Steps In Signaling
NSLP	NSIS Signaling Layer Protocol
NSP	Network Service Provider
NTM	Network Topology Manager
NTLP	NSIS Transport Layer Protocol
NWG	Network Working Group
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OID	Object Identifier
ONSI	Other Network Specific Information
OSS	Operational and Support Systems
PAN	Previous Access Network
PB	Petabytes
PCF	Point Coordination Function

PDCP	Packet Data Convergence Protocol
PDG	Packet Data Gateway
PDN-GW	Packet Data Network Gateway
PDP	Packet Data Protocol
PDU	Packet Data Unit
PHB	Per-hop Behavior
PLME	Physical Sublayer Management Entity
PLMN	Public Land Mobile Network
PMIP	Proxy Mobile IP
PoA	Point of Attachment
PoASI	Point of Attachment Specific Information
PoS	Point of Service
PS	Physical Slot
PSD	Packet Switched Domain
PSTN	Packet Switched Telephone Network
PTIN	Portugal Telecom Inovação
PtMP	Point to Multipoint
PtP	Point to Point
PTP	Precision Time Protocol
QAA	QoS Authorization Answer
QAR	QoS Authorization Request
QAM	Quadrature Amplitude Modulation
QMS	QoS Management Service
QNE	QoS NSIS Entity
QNI	QoS NSIS Initiator
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
QSPEC	QoS Specification object
RAN	Radio Access Network
RCM	Radio Configuration Manager
RCMS	Radio Channel Management Interface
RCSA	Redline Communications Specific Adapter
RAT	Radio Access Technology
REG-REQ/RSP	Registration-Request/Response
REP-REQ/RSP	Report-Request/Response
RM	Resource Manager
RMF	Resource Management Function
RNC	Radio Network Controller
RNG-REQ/RSP	Ranging-Request/Response
RO	Resources Occupancy
ROCP	Resources Occupancy Control Point
RNS	Radio Network System
RP	Reference Point
RRC	Radio Resource Control
RRM	Radio Resource Manager
RS	Relay Station
RSSI	Received Signal Strength Indicator
RTI	Resources Threshold Interval
RTP	Real Time Protocol
rtPS	real-time Polling Service
RTSP	Real Time Streaming Protocol
SAE	System Architecture Evolution
SANI	Service Access Network Interface
SAP	Service Access Point
SBC-REQ/RSP	SS Basic Capabilities-Request/Response

SC	Service Class
SCM	Service Class Manager
SDP	Session Description Protocol
SDU	Service Data Unit
SF	Service Flow
SFID	Service Flow Identifier
SFM	Service Flow Manager
S-GW	Serving Gateway
SGSN	Serving GPRS Support Node
SHO	Soft Handover
SIP	Session Initiation Protocol
SLA	Service Level Agreement
SLS	Service Level Specification
SME	Station Management Entity
SNCI	Static Network Context Information
SNMP	Simple Network Management Protocol
SNR	Signal to Noise Ratio
SOA	Service Oriented Architecture
SS	Subscriber Station
SSID	Service Set Identifier
STA	Session Termination Answer
STCI	Static Terminal Context Information
STR	Session Termination Request
SU-O	Subscriber Unit Outdoor
SVC	Scalable Video Coding
TAN	Target Access Network
TCIS	Terminal Context aware Information Server
TCP	Transmission Control Protocol
TCM	Thresholds Configuration Manager
TDD	Time Division Duplex
TDM	Time Division Multiplex
TDMA	Time Division Multiple Access
TFTP	Trivial File Transfer Protocol
TMS	Terminal Management Service
ToS	Type of Service
TSM	Terminal Status Manager
UA	User Agent
UC	University of Coimbra
UCD	Uplink Channel Descriptor
UDP	User Datagram Protocol
UE	User Equipment
UGS	Unsolicited Grant Service
UHF	Ultra-High Frequency
UL-MAP	Uplink Map
UMIP	USAGI-patched Mobile IPv6 for Linux
UMTS	Universal Mobile Terrestrial System
UTRAN	Universal Terrestrial Radio Access Network
VBR	Variable Bit Rate
VHOPR	Vertical Handover Policies Repository
VLAN	Virtual Local Area Network
VLR	Visited Location Register
VoIP	Voice Over IP
VSA	Vendor Specific Adapter
WA	WiMAX Agent
WCDMA	Wideband Code Division Multiple Access

WEIRD	WiMAX Extension to Isolated Research Data networks
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide interoperability for Microwave Access
WLAI	WiMAX Legacy Applications Interface
WLAN	Wireless Local Area Network
WLI	WXLM Link Interfaces
WMAN	Wireless Metropolitan Area Network
WNI	WXLM Network Interface
WT	WiMAX Terminal
WXLM	WiMAX Cross Layer Manager

1. Introduction

This chapter starts by presenting the motivation for conducting a PhD Thesis in the area of Broadband Wireless Access (BWA) networks (section 1.1). Following the motivation, the open research challenges of this topic are identified and the ones addressed on this Thesis are thoroughly described in section 1.2. Subsequently, the specific objectives to be pursued during the PhD are highlighted in section 1.3, as well as the main scientific and industrial outcomes in section 1.4. In conclusion, section 1.5 presents the document structure.

1.1. Motivation

For several years now, service providers, network operators and equipment manufacturers are grappling with the great challenge of the convergence of communication between networks and services. The explosion of broadband access in both wired and wireless regimes, on the one hand, and the adoption of bandwidth demanding network services accelerated this convergence. Ultimately, this will lead to a network capable of delivering voice, data, multimedia content, video communications and video broadcasting services – a real multimedia world of services centered on the user.

Ubiquitous Internet access is one of the main challenges for the telecommunications industry. The number of users accessing the Internet is growing at a very fast pace. At the same time, the average customer uses more than one device to connect to the Internet, and downloads and uploads digital media of an unprecedented magnitude. The network access paradigm of "always best connected, anytime, anywhere" is a central requirement for the so-called Next Generation Networks (NGN) [1] [2] [3], defined by the International Telecommunications Union – Telecommunication Standardization Section (ITU-T) [4]. Such a requirement places a tall order to operators that ought to find ways to provide broadband connectivity to their subscribers independently of their location and access device. Furthermore, the popularity for high-bandwidth services (including those arising from social networking sites) and other demanding multimedia applications is expected to continue to increase. This will lead the mobile communications revolution illustrated in Figure 1-1.

The recent architectural efforts made by several standardization organizations and groups (Internet Engineering Task Force – IETF [5], Institute of Electrical and Electronics Engineers – IEEE [6], European Telecommunications Standards Institute – ETSI [7], WiMAX Forum [8], ITU-T [4], 3rd Generation Partnership Project – 3GPP [9], etc.) are focused in enhancing the existent architectures or defining new ones, targeting (among others), two major objectives: (i) support of seamless interworking of different heterogeneous lower layer technologies (wireline/wireless, mobile/fixed), and (ii) unification and integration of the logical framework for high level services and applications. "All IP" is a unifying paradigm to allow uniform but flexible processing at higher layers. Horizontal architectural decomposition in multiple planes offers better possibility to control and manage the network and services entities.

Recognizing IP as a basis for integration in NGN, the ITU standardization body defined the NGN as an enhanced IP-based network and services architecture. The starting point was that new applications have new needs, not fulfilled by the traditional IP architecture. Consequently, the ITU-T standardization sector identified a number of key features necessary in an NGN [1], as well as a general framework for the architecture [2]. As defined in [1], a NGN can is defined as follows:

> *"A packet-based network able to provide telecommunication services and able to make use of multiple broadband, QoS-enabled transport technologies and in which service-related functions are independent from underlying transport-related technologies. It enables unfettered access for users to networks and to competing service providers and/or services of their choice. It supports generalized mobility which will allow consistent and ubiquitous provision of services to users."*

The main NGN step beyond traditional telecommunications architectures is the shift from separate vertically integrated application-specific networks to a single network capable of carrying all services. Circuit switching migrates to IP packet switching, but still NGN is capable to offer services with quality comparable to the telecom one. Additionally, sophisticated applications and services are possible, by introducing the IP Multimedia Subsystem (IMS) [10] based on the Session Initiation Protocol (SIP) [11] framework. The transport envisaged by NGN is assured by multiple broadband Quality of Service (QoS) enabled transport technologies, while the high level service-related functions are independent of this transport. Such an approach enables flexible access for users to networks and competing service providers and/or services of their choice. It also supports generalized mobility that will allow consistent and ubiquitous provision of services to users.

Figure 1-1 illustrates the new paradigm for the mobile networks, driven by three main factors: (i) bandwidth demanding services, (ii) high capacity Radio Access Technologies (RAT) and (ii) advanced Mobile Node (MN).

Figure 1-1: New mobile communications paradigm

Traffic volume in the current Internet is expected to rapidly increase and become an order of magnitude larger in the foreseeable future. According to Cisco estimates [12], the average mobile broadband subscriber recorded monthly traffic is of 0.24 Exabytes (EB) in 2010. Cisco expects that this average will grow almost 26-fold to more than 6.3 EB by 2015. Mobile video, as illustrated in Figure 1-2, will play a dominant role in this traffic increase – of the 6.3 EBs per month crossing the mobile network by 2015, 4.2 EBs will be due to video, and can only be handled by fresh infrastructure investments and thus even bigger electricity bills for operators.

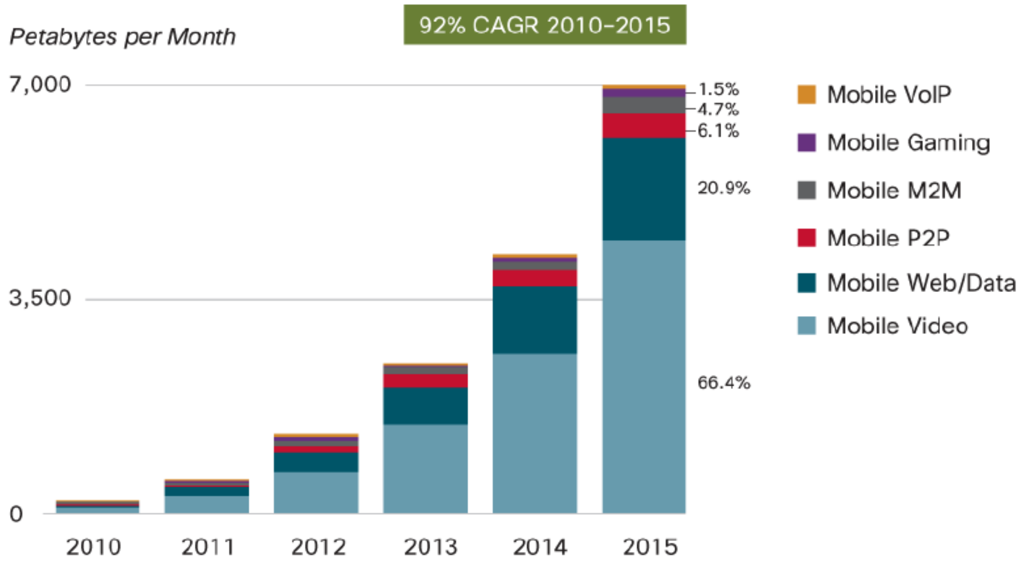

Figure 1-2: Mobile services traffic forecast until 2015 [12]

It is necessary to mention the forecasted increase in global mobile data traffic when referring to bandwidth limitations and the impact of smartphones (Figure 1-3). Notably, mobile traffic will reach over 2000 Petabytes (PB) per month by 2013 and mobile video, driven by smartphones, netbooks and laptops will be responsible for the majority of the traffic growth. By 2015, the mobile data traffic footprint of a single subscriber could be 450 times what it was 10 years earlier in 2005. Comparing this with 1 PB mobile traffic in 2005, it shows the tremendous traffic increase in mobile networks. The Next Generation Network Mobile (NGMN) Alliance reports that smartphone users in Europe on platforms such as the iPhone and Android currently generate over 15 times more data usage than basic feature phone subscribers. As depicted in [12], the forecasted data traffic growth stems primarily from increase in mobile video. Figure 1-3 shows the MNs responsible for the mobile data traffic growth. In 2015, laptops will continue to dominate this sector, however, with a rapid rise of smartphones. It is also important to mention the emergence of home gateways, Machine-to-Machine (M2M) devices and tablets.

From the RATs point of view, the large-scale investments made in mobile telecommunications over the past decade have led to a wide variety of solutions for wireless Access Networks (AN). Metropolitan areas initially saw extensive use of 3G [13], via the Universal Mobile Telecommunications System (UMTS) technology [14], followed by the introduction of High Speed Packet Access (HSPA) [15] technology which gave rise to 3.5G. Although 3.5G offered higher speeds, these were not yet high enough to encourage the appearance of real-time services for mobile terminals of growing sophistication and increased potential. This, in turn, led to migration to the 4G paradigm [13] [16], with the introduction of Long Term Evolution (LTE) [17] [18] and Worldwide Interoperability Microwave Access (WiMAX) [19] [20] [21], recognized by ITU as the de-facto 4G compliant access technologies [22]. At the same time, and in terms of local areas, Wireless-Fidelity (Wi-Fi) [23] continued to dominate and consolidate its position in the market, complementing the 3G (UMTS), 3.5G (HSPA) and 4G (LTE and WiMAX) metropolitan wireless networks.

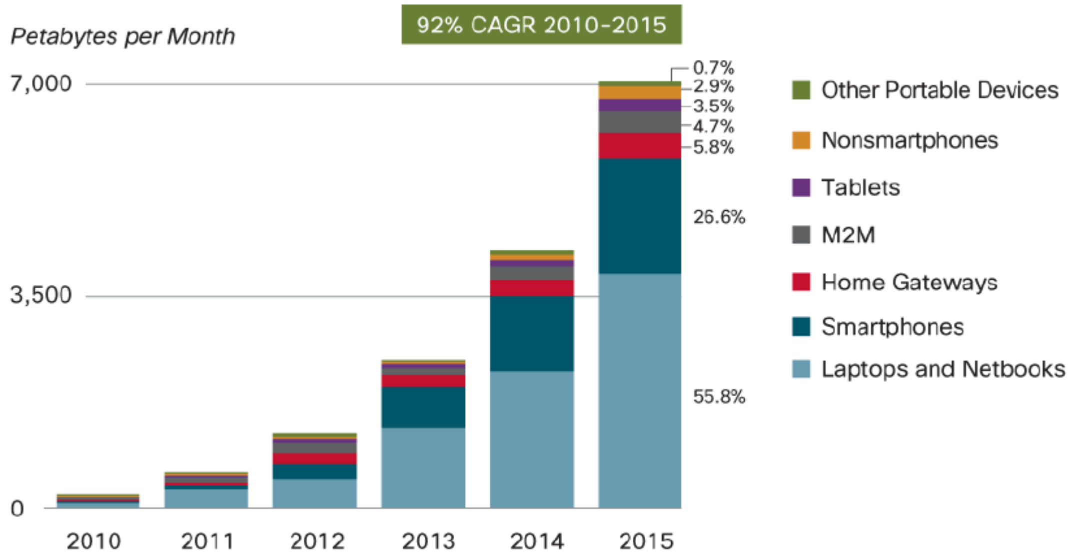

Figure 1-3: Mobile terminals traffic forecast until 2015 [12]

Undoubtedly, WiMAX and UMTS/LTE for metropolitan areas and Wi-Fi as a complement for local areas will be the RATs that will occupy the wireless network domain in the next decade. For this reason, these technologies have been the subject of numerous discussions within the standardization bodies and the scientific community to prepare them adequately for the NGNs paradigm. However, there is still a long way to go before these technologies are fully prepared for the challenges posed by next generation mobile communications and are thus successfully adopted.

Part of the research carried out on this Thesis focuses on WiMAX, since it is one of the most promising technologies for metropolitan environments. To highlight this trend, several telecommunication operators from the five continents are investing on this technology for fixed and mobile scenarios. In the case of Portugal Telecom Inovação (PTIN) [22], this commitment is evidenced through the membership in standardization bodies, in particular the WiMAX Forum, through the participation and contribution for international collaboration projects co-financed by the European Commission, such as Designing Advanced network Interfaces for the Delivery and Administration of Location independent, Optimized personal Services (DAIDALOS I / II) [25] [26], WiMAX Extension to Isolated Research Data networks (WEIRD) [27] and Handover for Ubiquitous and optimal bRoadband connectIvity among CooperAtive Network Environments (HURRICANE) [28], and also through the development of a WiMAX compliant prototype on the PTIN premises. PTIN can, for example, provide management and control solutions for WiMAX based AN deployments.

WiMAX has some gaps in order to be considered a technology ready for use in NGN environments. Specifically, the delivery of multimedia services with real-time characteristics, which implies an effective management of the WiMAX QoS procedures, as well as its integration with IP level QoS mechanisms, is one of the subjects of study. Another important feature to improve in this technology is related with the seamless (micro and macro) mobility mechanisms between WiMAX antennas, thus allowing the effective delivery of services without disruption to end-users as they move. This type of functionality is fundamental in a transparent communications paradigm, and may thus be a differentiating factor between the telecommunications operators.

Another major part of this Thesis focuses on the coexistence of WiMAX with other wireless ANs (e.g. Wi-Fi, UMTS/HSPA and LTE). Taking into account the wireless domain heterogeneity, where multiple RATs will cohabit and benefit the communication with the end-user, it is essential for telecom operators to be prepared for the challenges posed by these environments. PTIN can, for example, be a leading supplier for heterogeneous wireless ANs, providing connectivity and mobility management solutions to accomplish the "*always connected, anytime, anywhere*" paradigm. Such domains allow the MNs to automatically connect to the best available wireless AN, at any given moment. From the operator’s point of view, given the increasing shortage of resources in mobile broadband ANs and the proliferation of Wi-Fi hotspots, automatic offloading to Wi-Fi allows operators to optimize the radio resources of these networks and, simultaneously, to make the most of their Wi-Fi hotspots.

Taking into account the wireless domain heterogeneity, where multiple RATs will cohabit and benefit the communication with the end-user, it is essential to define mechanisms and procedures to ensure the coexistence of these technologies in these environments. This way, it is critical to provide mechanisms for seamless mobility between different access technologies (e.g. WiMAX, Wi-Fi, UMTS/HSPA and LTE), considering the end-user's characteristics, as well as the network itself. This is a hot topic and, as such, has been receiving much attention from the standardization bodies and the academia. Nevertheless, there are still gaps that must be solved.

The various open issues referred above were the major motivation for the development of this Thesis. Section 1.2 identifies these issues in detail and discusses the research challenges addressed in this PhD.

1.2. Research Challenges

To be able to present and describe the research challenges that were addressed in this Thesis, it is important to briefly describe the main NGN characteristics.

Figure 1-4 illustrates the NGN architecture.

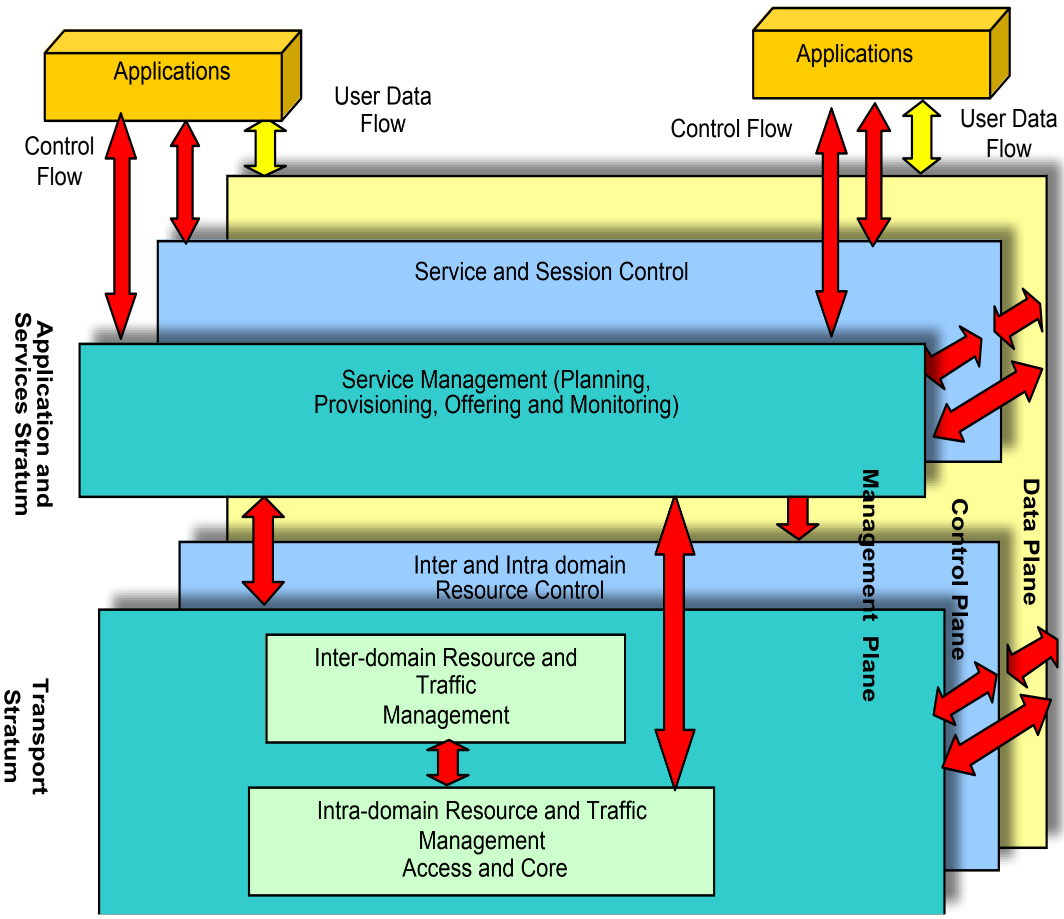

Figure 1-4: NGN architecture overview [29]

The NGNs can be defined by the following fundamental characteristics [1] [2]:

- Packet-based transfer;
- Separation of control functions among bearer capabilities, call/session, and application/ service;
    - Independence of service-related functions from underlying transport technologies;
    - Decoupling of service provision from transport;
- Support for a wide range of services, including real time, streaming, non-real time and multimedia services;
    - Unified service characteristics for the same service as perceived by the user;
- Broadband capabilities with end-to-end QoS;
    - Support of multiple last mile technologies;
- Interworking with legacy networks via open interfaces;
- Generalized mobility;
    - Converged services between fixed/mobile;
- Unrestricted access by users to different service providers;
    - Multiple identification schemes;
- Compliant with all regulatory requirements, for example concerning emergency communications, security, privacy, lawful interception, etc.

From the NGN fundamental characteristics described above, as well as from the expectable mobile telecommunications revolution, a main set of challenges were identified as critical for the successful migration towards the new mobile communications paradigm and therefore identified as key research topics to be addressed on this Thesis. The following subsections depict each one of the identified research challenges.

1.2.1. QoS Control for an All-IP WiMAX Network Architecture

Supporting multimedia applications with stringent QoS requirements (e.g. high throughput, minimum latency and minimum packet loss) is one of the most challenging issues for WiMAX based ANs.

For the successful delivery of a real-time service to the end-user, it is necessary to ensure QoS support at the link layer, either wired or wireless, as well as at the IP-layer. For wireless access technologies, such as WiMAX, the QoS support requirement is even more important given the shortage of resources in the wireless media. WiMAX intrinsically supports QoS by using a connection-oriented approach. A unique Connection Identifier (CID) is assigned to each uplink/downlink connection pair at the WiMAX Medium Access Control (MAC) layer before any data transmission takes place over the air interface. A CID serves as a temporary address for the transmitted data packets over the WiMAX link. For the WiMAX Base Station (BS) to manage the QoS requirements of individual data flows, the same Service Flow Identifier (SFID) is assigned to unidirectional packet flows which have the same QoS parameters. As basically the serving BSs centrally control all wireless connections in WiMAX, it is reasonable to implement also the QoS control functionality at the BSs. After all, it is the BS that handles the mapping between SFIDs and CIDs. Currently, the MAC layer of a WiMAX BS includes support for five different QoS classes which can be used to adjust system behavior to be more favorable to different traffic types and applications.

At the network level, several QoS provisioning models and protocols have already been defined and studied to efficiently deliver end-to-end QoS multimedia applications. Two main approaches have been proposed to achieve QoS support at the IP level, namely, the Integrated Services (IntServ) [30] and the Differentiated Services (DiffServ) [31]. While the former has shown scalability problems, the later is used in networks to provide qualified applications the service level that is adequate for their requirements.

End-to-end QoS support needs to resort to a signaling protocol in order to convey the resource reservation requests along the network. The Next Steps in Signaling (NSIS) [32] framework has been conceived in order to support network signaling, with QoS signaling as its first application. The NSIS framework comprises two layers, namely, the NSIS Transport Layer Protocol (NTLP) and the NSIS Signaling Layer Protocol (NSLP) [33]. The NTLP layer, also known as General Internet Signaling Transport (GIST) [34] is responsible for the transport of the signaling messages sent by NSLPs. The NSLP layer is specific to each application. The first NSLP defined, named QoS-NSLP, was designed to provide resource reservation signaling support.

As described above, QoS standardized mechanisms for both network layer and WiMAX link layer are already in place. However, one of the major gaps is the **inter-layer connectivity, also known as cross-layer, between the network and the link layer functions to establish the required QoS pipes in the WiMAX link according to the upper layer QoS protocols and control entities**. The ways in which different end systems can reach an agreement on the end-to-end QoS for a session and how the parameter sets of the upper layer QoS protocol can be used to dynamically control the resources allocation on the WiMAX link layer need to be defined. Furthermore, **monitoring procedures for the WiMAX link layer are necessary to perform admission control and manage the resources availability**. Summarizing, the cross-layer communication between the IP level QoS entities and WiMAX is a critical issue to achieve end-to-end QoS and therefore successfully deliver multimedia services. The **WiMAX network management and its integration with the network level QoS control entities** is one of the research topics addressed on this Thesis.

The abovementioned research challenges will be addressed in chapter 4 of this Thesis.

1.2.2. Seamless Mobility Support in WiMAX Access Networks

RATs provide their own mechanisms for mobility at the link layer level, allowing mobile terminals to move freely in geographical areas whose BSs belong to the same IP domain. WiMAX, more precisely IEEE 802.16e [20], provides a set of procedures to address the mobility at the link layer level, namely:

- Hard Handover (HHO): this method is simpler and is mandatory, that is, must always be provided by implementations of the manufacturers; in this type of handover the MN is disconnected from the serving BS and then binds to the target BS; since the MN remains disconnected during the handover, it is likely that there is packet loss and, therefore, this method is commonly known as *break-before-make*;
- Macro Diversity Handover (MDHO) and Fast Base Station Switching (FBSS): these methods are of type *make-before-make*, that is, the MN initiates communication with the target BS before being disconnected from the serving BS; given that the MN is connected to both serving and target BS, these two procedures do not have gaps in communications with the MN.

IEEE 802.16 specifies the communication between the BS and the MN using a set of MAC management messages. Nevertheless, IEEE 802.16 does not specify the communication between the serving and the target BSs in the backbone network. This communication link is very important to transfer the context information between the serving and the target BSs. To fill this gap, the WiMAX Forum has specified a network protocol that establishes the communication between the serving and the candidate BSs for the handover procedure.

At the network level, several IP mobility management protocols are already available and standardized to solve the mobility problem by intercepting and redirecting packets to the new location of the MN. Through the presence of mobility agents, the Mobile IP (MIP) protocol [35] [36] detects the MN movement, provides him a new IP address and intercepts and redirects the data packets to the MN. Apart from the basic version of the IP mobility management protocol, other versions have been released to fill the gaps raised by the basic MIP version (e.g. high latency, packet loss and signaling overhead). For example, the Fast MIP (FMIP) [37] sought to accelerate procedures for detecting the MN movement. Any of the above mentioned mobility management protocols are host-based and therefore require the intervention of the MN for its operation. An alternative solution, called Proxy MIP (PMIP) [38], requires no intervention on the MN side since all mobility management procedures are made at the network level entities.

As described in the preceding paragraphs, there are already mobility mechanisms defined for the WiMAX link layer, as well as for the IP level. However, it is not possible to achieve seamless mobility, that is, mobility without services disruption, based only on single-layer solutions. Rather, it is essential to integrate these "two worlds" through cross-layer mechanisms, since both depend on each other to be able to make their processes more efficient.

More specifically, cross-layer mobility procedures are very important for two main reasons. The first one is to notify the upper layer mobility control entities about the WiMAX link layer modifications. A typical example of WiMAX link layer events sent towards the IP level mobility agents is to indicate to the upper layer that the MN is moving towards the border of the cell and therefore loosing coverage. The WiMAX mobility trigger should be generated in time to allow the IP layer to act properly and in parallel to the mobility processes of WiMAX link layer. Otherwise, it will not be possible to obtain good results for the complete mobility process. The second important reason for the necessity of inter-layer mobility procedures is related with the need of the upper layer mobility agents to query and enforce mobility decisions on the WiMAX link layer. Therefore, beyond the cross-layer events towards the upper layer, cross-layer commands towards the WiMAX link layer are also required. Briefly, the combination of bidirectional cross-layer mobility mechanisms enables the fusion of mobility procedures from both layers, crucial to obtain WiMAX seamless mobility procedures.

IEEE defined the 802.21 [39] standard to enable Media Independent Handover (MIHs). IEEE 802.21 defines an abstract framework which delivers link layer information to the higher layers, in an effort to optimize handovers between homogeneous and heterogeneous media, aspiring to harmonize mobility management processes between link layer access technologies and the IP level mobility management protocols, irrespective of the underlying technologies.

Although the work within the IEEE 802.21 working group is already in an advanced stage, the framework needs to be integrated with each specific access technology, since each one has its particular mobility control procedures. **For WiMAX, it is required the translation of the IEEE 802.21 generic primitives, either events and/or commands, to the specific WiMAX management primitives. Within this integration process, new IEEE 802.21 and/or WiMAX primitives will be required and modifications to existing ones will also be necessary.**

Beyond the events and command services provided by the IEEE 802.21 framework, it also provides a protocol to establish the communication between several network elements (e.g. MN, AN and Core Network – CN). Nevertheless, no specific transport mechanism is defined to carry the IEEE 802.21 protocol messages between the remote peers. **Therefore, it is also required to select or define a transport protocol to carry the IEEE 802.21 messages along the network entities.**

Another key requirement during a seamless handover procedure is QoS support. To ensure high-quality service delivery after the handover execution process to the new AN, it is required to **establish the QoS reservations on the target WiMAX link layer, as well as at the end-to-end path, through the interaction with the upper layer QoS management protocols**. This way, it is assured that when the MN connects to the new AN, the end-to-end and WiMAX specific resources are already assigned and ready to be used by the MN.

Seamless handover mechanisms require a set of phases, such as movement detection, neighbor networks discovery, target network selection and handover execution that must be synchronized and controlled by a single central entity. Furthermore, it is also required that this mobility control entity, also known as Mobility Manager (MM), controls the interfaces with the mobility and QoS management protocols. Therefore, to achieve WiMAX seamless mobility, it is necessary to **define a WiMAX mobility management entity running on both the network and terminal side**.

The abovementioned research challenges will be addressed in chapter 5 of this Thesis.

1.2.3. Optimized Fusion of Heterogeneous Wireless Access Networks based on Media Independent Handover Operations

Fixed-mobile convergence trend suggests that the end-user will be able to attain "any service" on a single hand-held device using any available network that is optimized for the application at hand. Thus, the new communications vision is targeting the integration of Internet, cellular and broadcasting services bringing the user fully in touch with the information age, whilst creating new market opportunities for content service providers and telecom manufacturers.

A key fixed-mobile convergence driver is to provide ubiquitous high-speed wireless connectivity to mobile multimode terminals using cost-effective techniques. In such an environment, it will be necessary to support seamless mobility without causing disruption to ongoing sessions. Seamless mobility means providing the ability of using different access technologies, at different locations while the user and/or the terminal equipment itself may be in movement allowing users to use and manage consistently their services across existing network boundaries. This vision requires a cooperative wireless AN that shares system information and assists in handover events resulting in a seamless end-user experience irrespective of the application at hand.

The mobility processes can be classified into two major groups: (i) horizontal mobility (or intra-technology) in which mobile terminals move in areas covered by the same access technology, (ii) vertical mobility (or inter-technology) in which MNs move between different access technologies (e.g. between Wi-Fi and WiMAX).

After having identified the research challenges related to mobility in WiMAX homogeneous environments (section 1.2.2), the scope of the Thesis is extended to address the challenges posed by end-user service continuity in heterogeneous access environments comprised by WiMAX, Wi-Fi, UMTS/HSPA and LTE access technologies.

While the basic idea behind the concepts just mentioned is clear and agreed, its realization offers numerous yet unsolved challenges. At this point in time, the standardization organizations have specified basic mobility support between heterogeneous networks. The mobility is, however, not yet seamless. The challenges posed by vertical mobility procedures are similar to the ones depicted for WiMAX horizontal mobility described in section 1.2.2. However, despite the fact that the kind of challenges is identical, the complexity is higher since we are dealing with multiple wireless access technologies, each with its specific characteristics. On the other hand, the entities responsible for QoS and mobility management must be located at the IP layer to interact with various access technologies, instead of being positioned within each radio access technology.

As for the WiMAX horizontal mobility procedures, one of the open research topics is the **integration of IEEE 802.21 based cross-layer mechanisms with each one of the access technologies (Wi-Fi, UMTS/HSPA and LTE)**. The IEEE 802.21 cross-layer integration makes it possible to decrease the inter-technology handover latency.

For each of the identified RATs, it is necessary to **translate the generic IEEE 802.21 primitives (commands and events) to the primitives and parameters of each specific access technology** that comprise the wireless heterogeneous environment. To control the whole mobility process, including the discovery and communication with neighboring access technologies, the selection of the most appropriate Candidate AN (CAN) and also the interaction with the relevant QoS control entities, it is necessary to **define a vertical handover, IEEE 802.21 enabled, MM**.

Finally, as in the intra-technology WiMAX mobility case, it is mandatory to **integrate the inter-technology mobility procedures with the end-to-end QoS reservation protocols**. Furthermore, the inter-technology mobility procedures should also **interact with the cross-layer QoS reservation mechanisms for each access technology**.

The abovementioned research challenges will be addressed in chapter 6 of this Thesis.

1.2.4. Context-aware Media Independent Handovers

The ubiquity of mobile devices opens our computing and communication environment to a rapidly changing world where people have tremendous capabilities to utilize these devices for innovative social and cognitive activities. Driven by these advances, not just our working style, but also our social attitude has and will continue to change. From arranging a virtual video conferencing with a colleague, friend or group of friends to arranging a face to face meeting, from mobile gaming zones to mobile sharing and from emergency services to sought-after tourist services, the trend of future applications and services is apparent. Communication is not just about high-speed network or devices but about personalization, context-awareness and seamless mobility.

Today's mobility decisions are based on very limited information, such as the Signal to Noise Ratio (SNR). In heterogeneous wireless environments, this input is clearly insufficient and ineffective for the decision algorithms. **Multiple sources of information, retrieved from the terminal/user and/or from the network side, are required by the vertical handover decision algorithms** to successfully control the handover procedure and select the most appropriated moment and target network for the handover. The context information can be dynamic (e.g. battery level, running service, velocity, ...) or static (e.g. device capabilities, cost, interface preferences, ...), and its integration in the vertical handover procedures is challenging for several reasons. One of the most challenging topics is to define **the most suitable place to**

store and process the context information within the mobility architecture, and the most appropriate **procedure to transport the context information** from context providers to the place of storage.

Finally, it is also important to **assess the impact that the integration of context information in the handover decision algorithms has on the inter-technology mobility procedures**, particularly in each one of the mobility phases (initiation, preparation, execution and termination).

The abovementioned research challenges will be addressed in chapter 7 of this Thesis.

1.3. Objectives

Given the gaps presented previously in section 1.2, herein is thoroughly described the main objectives foreseen on this Thesis in each one of the identified key research topics:

- QoS control for an All-IP WiMAX network architecture;
- Seamless mobility support in WiMAX ANs;
- Optimized fusion of heterogeneous wireless ANs based on MIHs;
- Context-aware MIHs.

The macro and micro objectives are as follows.

1.3.1. QoS Control for an All-IP WiMAX Network Architecture

To tackle the challenge of end-to-end QoS support for multimedia services in WiMAX ANs, the following objectives were identified:

- Define a WiMAX cross-layer framework to enable the complete control (e.g. network topology discovery, QoS and radio resources management, equipment vendors independency, …) and communication of WiMAX systems with the upper layer network entities;
- Integrate the WiMAX cross-layer framework in an end-to-end all-IP QoS provisioning WiMAX architecture, comprising control, management and data plane functions, with support for legacy and multimedia applications;
- Specify detailed message sequence charts for the integrated WiMAX QoS management procedures;
- Implement the WiMAX cross-layer framework and integrate with the remaining entities of the WiMAX QoS-enabled architecture;
- Evaluate the QoS management procedures performance of the WiMAX all-IP architecture through a network prototype integrated in a real operator scenario.

1.3.2. Seamless Mobility Support in WiMAX Access Networks

With regard to the seamless mobility support in WiMAX ANs, the following objectives were identified:

- Extend the end-to-end all-IP QoS-enabled WiMAX architecture with generic media independent seamless mobility control mechanisms;
- Extend the WiMAX cross-layer framework with mobility services at the terminal and the network side, namely generic and media independent link layer events and commands, enabling both terminal and network initiated handovers;
- Extend and translate the WiMAX RAT primitives to the IEEE 802.21 specific link layer primitives;
- Integrate the WiMAX QoS and mobility enabled architecture with the most suitable transport protocol to carry the MIH messages between remote network elements;
- Specify detailed message sequence charts for the WiMAX QoS and mobility architecture in a macro-mobility scenario;
- Implement the required mobility extensions for the WiMAX cross-layer framework and integrate with the remaining entities of the WiMAX QoS-enabled architecture;

- Evaluate the integrated QoS and mobility management procedures performance of the WiMAX all-IP architecture through a network prototype integrated in a real operator scenario.

1.3.3. Optimized Fusion of Heterogeneous Wireless Access Networks based on Media Independent Handover Operations

After having identified the research challenges related to mobility in homogeneous environments composed by the WiMAX technology, the scope of the Thesis is extended to address the challenges posed by end-user service continuity in heterogeneous access environments comprised by WiMAX, Wi-Fi, UMTS/HSPA and LTE. The following objectives were identified:

- Define an heterogeneous access architecture with support for seamless mobility and QoS procedures, able to support several types of wireless access technologies, such as Wi-Fi, WiMAX, UMTS/HSPA and LTE;
- Integrate the WiMAX QoS and mobility enabled architecture within the mobility heterogeneous architecture components;
- Extend the IEEE 802.21 MIH framework with radio resources management capabilities during mobility procedures;
- Extend and translate the Wi-Fi and UMTS/HSPA RATs primitives to the IEEE 802.21 specific link layer primitives;
- Extend the WiMAX cross-layer framework with inter-technology mobility services at the terminal and the network side, namely with media independent radio resources management;
- Specify detailed message sequence charts for seamless inter-technology handover procedures with support for the proposed cross-layer media independent radio resources management primitives and the MIH translation procedures;
- Implement the required inter-technology mobility extensions for the WiMAX cross-layer framework and integrate with the remaining entities of the heterogeneous network architecture;
- Evaluate the inter-technology mobility architecture performance through a network prototype integrated in a real operator scenario, as well as in a large-scale environment through simulations.

1.3.4. Context-aware Media Independent Handovers

Finally, regarding the context-aware mobility decisions, the following set of objectives was identified:

- Extend the heterogeneous seamless mobility architecture with context-aware information to optimize handover decisions;
- Define the MIH Context-aware Information Server (CIS);
- Specify detailed message sequence charts for inter-technology seamless handover procedures optimized with context-aware information;
- Implement the required mobility extensions for the context-aware information handover procedures and integrate with the remaining entities of the heterogeneous network architecture;
- Evaluate the inter-technology context-aware mobility architecture performance through a network prototype integrated in a real operator scenario, as well as in a large-scale environment through simulations.

Further details about the abovementioned objectives will be exhaustively detailed in each one of the Thesis chapters.

1.4. Contributions

Hereafter, the set of contributions provided by this Thesis are briefly discussed, alongside with the scientific publications in workshops, conferences and journals, as well as the industrial contributions, more precisely patents, PTIN internal prototypes and products.

Initially, as a motivation and rationale for the work developed in this Thesis, a set of reference scenarios with potential interest from the standpoint of a telecom operator are presented and discussed. Novel and futuristic BWA scenarios for both fixed and mobile access environments using local (e.g. Wi-Fi) and metropolitan (e.g. WiMAX and LTE) RATs were defined. Furthermore, to assess the suitability of WiMAX for a fire prevention scenario, a fixed WiMAX-compliant testbed was installed in the Portuguese mountains, more precisely in the area of Lousã.

Further details about the proposed BWA reference scenarios are given in chapter 3. Table 1-1 presents the Thesis contributions related with the BWA reference scenarios.

Table 1-1: Publications on BWA reference scenarios

Type	Date	Title	Target
Conference	Dec 2006	Extending WiMAX to Novel and Stringent Wireless Scenarios: An Introduction to the WEIRD Project	Broadband Europe
Conference	Mar 2007	WiMAX technology support for applications in environmental monitoring, fire prevention and telemedicine	IEEE Mobile WiMAX Symposium
Workshop	Sept 2007	WiMAX for Emergency Services: An Empirical Evaluation	IEEE BWA (collocated with IEEE NGMAST)
Conference	Dec 2007	E-health Broadband Drivers for WiMAX Extension to Isolated Research Networks	Broadband Europe
Workshop	Jan 2008	WEIRD – Real Use Cases and Applications for the WiMAX Technology	IEEE BWA (collocated with IEEE NGMAST)
Book Chapter	Jan 2009	Novel WiMAX Scenarios for Future Broadband Wireless Access Networks	WiMAX Evolution: Emerging Technologies and Applications (Wiley)
Book Chapter	Mar 2010	Multimedia Services over WiMAX	Advances in Computers: Improving the Web (Elsevier)

1.4.1. QoS Control for an All-IP WiMAX Network Architecture

In order to provide the mobile users with the requested multimedia services and the requested end-to-end QoS requirements, the WiMAX access technology QoS procedures have to be integrated with the IP/network level QoS architectures and protocols. To establish an efficient bidirectional communication between the network and the WiMAX system, it is proposed in this Thesis a **WiMAX cross-layer framework, called WiMAX Cross Layer Manager (WXLM), to enable the QoS control and communication of the WiMAX system with the upper layer network entities**. The WXLM is responsible for providing all the required cross-layer services and interfaces between the WiMAX system and the network layers to efficiently support end-to-end QoS and therefore multimedia applications.

The proposed WXLM comprises a middleware layer between the WiMAX technology and the network layer, isolating the WiMAX technology specific functionalities from the network control plane. The WXLM provides a dedicated service to "hide" and adapt the communications with the underlying WiMAX equipment – fixed and/or mobile, thus enabling the integration of any type of southbound interface, either standard (e.g. Simple Network Management Protocol – SNMP [40], WiMAX Forum, ...) and/or proprietary.

The defined **WXLM is integrated in an end-to-end all-IP QoS enabled architecture** in compliance with the WiMAX Forum guidelines. A northbound interface is provided by the WXLM to interact with the network layer QoS entities and/or protocols, and expose the WXLM services to the upper layers. For **end-to-end QoS support, the NSIS protocol is integrated to establish resources reservations** on the radio, access and CN segments.

The proposed architecture is **compliant with IMS using the SIP protocol** to establish end-to-end multimedia sessions. In addition to the support and integration with the IMS architecture, the proposed architecture also includes **support for legacy applications** that do not use any specific signaling protocol for establishing end-to-end sessions. Table 1-2 and Table 1-3 presents the Thesis contributions related with this research area.

Table 1-2: Publications on end-to-end QoS support for multimedia services (part I)

Type	Date	Title	Target
Workshop	Sept 2007	A Framework for Resource Control in WiMAX Network	IEEE BWA (collocated with IEEE NGMAST)
Conference	May 2007	Improving the Experience of Real Time Services in WiMAX Networks	ConfTele
Workshop	May 2007	Extending WiMAX Technology to Support End to End QoS Guarantees	WWM (collocated with IEEE WWIC)
Workshop	May 2007	Design and Experimental Evaluation of QoS and Mobility Support over Integrated 802.16 Metropolitan and Local Area Networks	WWM (collocated with IEEE WWIC)
Conference	Mar 2008	WEIRD Testbeds with Fixed and Mobile WiMAX Technology for User Applications, Telemedicine and Monitoring of Impervious Areas	TRIDENTCOM
Journal	Abr 2008	Establishing the First European Research WiMAX Testbed	ERCIM News – Mathematics for Everyday Life
Conference	May 2008	The Cost of Using IEEE 802.16 Dynamic Channel Configuration	IEEE ICC
Book Chapter	June 2008	WiMAX Extension to Isolated Research Data Networks: the WEIRD System	Mobile WiMAX (Wiley)
Conference	June 2008	A WiMAX QoS Model for NS2-NIST Framework	IEEE ICT
Conference	July 2008	A Vendor-Independent Resource Control Framework for WiMAX	IEEE ISCC
Conference	July 2008	Extending WiMAX to New Scenarios: Key Results on System Architecture and Testbeds of the WEIRD project	EUMOB
Journal	Sept 2008	Quality of Service and Mobility Support in WiMAX Networks	DETI-UA
Journal	Dec 2008	Design and Experimental Evaluation of QoS and Mobility Support over Integrated 802.16 MANs and 802.11 LANs	IEEE Vehicular Technology Magazine
Journal	Jan 2009	QoS Management and Control for an All-IP WiMAX Network Architecture: Design, Implementation and Evaluation	International Journal of Mobile Information Systems
Book Chapter	Jan 2009	A WiMAX Cross Layer Framework for Next Generation Networks	WiMAX Evolution: Emerging Technologies and Applications (Wiley)
Conference	May 2009	IEEE 802.16 Packet Scheduling with Traffic Prioritization and Cross-Layer Optimization	MOBILIGHT
Conference	May 2009	Evaluating WiMAX QoS Performance in a Real Testbed	ConfTele

Table 1-3: Publications on end-to-end QoS support for multimedia services (part II)

Type	Date	Title	Target
Book Chapter	Dec 2009	WiMAX Cross-Layer System for Next Generation Heterogeneous Environments	WiMAX, New Developments (In-Tech)
Book Chapter	Mar 2010	Quality of Service Differentiation in WiMAX Networks	Telecommunications Technologies (In-Tech)
Book	Nov 2011	IP Telephony Interconnection Reference: Challenges, Models and Engineering	CRC Press

Further details about the proposed end-to-end QoS-enabled WiMAX architecture are provided in chapter 4.

1.4.2. Seamless Mobility Support in WiMAX Access Networks

Once developed the necessary mechanisms to manage and integrate the WiMAX QoS procedures with the upper layers QoS entities and protocols, the second major contribution of this Thesis is to **extend the WiMAX QoS-enabled architecture with support for seamless mobility mechanisms**. For this, the WXLM is extended with the IEEE 802.21 platform in order to establish the bidirectional cross-layer mobility communication, that is, to support the exchange of IEEE 802.21 commands and events between the WiMAX system and the mobility management and control entities.

Another extension proposed to the **WXLM is a WiMAX Mobility Manager Service (MMS)** to control the handover decisions and the various stages of the handover process. The mobility features are made available by the WXLM on the network and on the terminal side, thus enabling support for mobile and network initiated and controlled handovers. Finally, for the successful integration of the IEEE 802.21 platform with WiMAX, it is **proposed the translation and mapping of the IEEE 802.21 primitives with WiMAX**, more specifically IEEE 802.16g [41]. As a result, it was required to set new primitives for both standards.

Finally, given the need to select a protocol to carry the IEEE 802.21 standard messages throughout the various IEEE 802.21 instances distributed in the MN and on the network side, it is **proposed an extension to the NSIS protocol to transport IEEE 802.21 messages**. The choice for the NSIS protocol to convey this information is due to the fact that this protocol is already used for exchanging QoS information. Furthermore, the NSIS framework meets the requirements posed by the IEEE 802.21 standard to carry its messages. Table 1-4 describes the Thesis contributions in this research area.

Table 1-4: Publications on seamless mobility support in WiMAX ANs

Type	Date	Title	Target
IETF Internet-Draft	Feb 2008	Media Independent Handover Network Signaling Layer Protocol (MIH-NSLP)	NSIS Working Group
Journal	Dec 2008	A Evolução da 3ª Geração Móvel, a Visão do 3GPP	PTIN – Saber & Fazer
Conference	Jun 2009	Mobility Architecture for NGN WiMAX: Specification and Implementation	IEEE WoWMoM
Conference	Oct 2009	Advanced Mobility in Broadband Wireless Access Scenarios	IEEE WiMOB
Book Chapter	June 2010	Mobility Management Architecture for WiMAX Networks	WiMAX Networks: Techno-Economic Vision & Challenges (Springer)
Conference	Sept 2011	IEEE 802.21 MIH-Enabled Evolved Packet Core System Architecture	Monami

Further details about the proposed cross-layer mobility extensions for WiMAX are depicted in chapter 5.

1.4.3. Optimized Fusion of Heterogeneous Wireless Access Networks based on Media Independent Handover Operations

After the QoS and mobility extensions proposed for WiMAX, the next major contribution of this Thesis is to **broaden the scope and address seamless mobility with QoS support in heterogeneous wireless access environments** composed by WiMAX, Wi-Fi, UMTS/HSPA and LTE.

An **architecture with seamless mobility support in heterogeneous wireless ANs is proposed**, with integration of the **IEEE 802.21 framework**, the **MIP mobility management protocol** and with support for **end-to-end QoS reservations through NSIS**. The WiMAX architecture proposed in the previous sections, with support for QoS and horizontal mobility mechanisms, is integrated with the seamless mobility architecture defined herein. To integrate the later with the Wi-Fi and UMTS/HSPA RATs, the **primitives from each access technology were studied and translated to the most appropriate IEEE 802.21 primitives**. After performing this mapping, some gaps were identified and new primitives were proposed to overcome the absence of some features, either from the RATs or by the IEEE 802.21 platform.

To take advantage of the IEEE 802.21 cross-layer mobility mechanisms, an **extension to the IEEE 802.21 platform is proposed in order to manage the QoS of the wireless access technologies**. Thus, instead of using two different cross-layer protocols for mobility and QoS, the IEEE 802.21 platform is used for both.

Finally, it is **proposed a vertical MM to control the handover process between different wireless access networks** involved in the handover (WiMAX, Wi-Fi and UMTS/HSPA). The vertical MM is responsible for controlling the various handover phases: initiation (e.g. MN movement detection), preparation (e.g. discovery of neighbor ANs, discovery of resources availability, selection of the Target AN (TAN) and radio resources enforcement), execution (e.g. IP level mobility management) and termination (e.g. radio resources elimination on the Previous AN – PAN).

Table 1-5 and Table 1-6 describe the Thesis contributions in this research area.

Table 1-5: Publications on optimized fusion of heterogeneous wireless ANs (part I)

Type	Date	Title	Target
Conference	July 2008	HURRICANE Handover Scenarios, Metrics and Testbeds	TEMU
Conference	July 2008	HURRICANE: 4G Vision with Seamless Mobility, Service Continuity and Network Interoperability in mind	TEMU
Journal	Dec 2008	Optimização dos Mecanismos de Mobilidade em Redes de Próxima Geração	PTIN – Saber & Fazer
Conference	April 2009	Enhanced Media Independent Handover Framework	IEEE VTC
Journal	April 2009	Optimized Fusion of Heterogeneous Wireless Networks Based on Media Independent Handover Operations	IEEE Wireless Communications Magazine
Conference	Jun 2009	Specification of Optimized Handover Operations among Cooperative Networking Environments	ICT Mobile Summit
Workshop	Dec 2009	Media Independent Handovers: LAN, MAN and WAN Scenarios	IEEE BWA (collocated with IEEE GLOBECOM)
Book Chapter	June 2010	Mobility Management Architecture for WiMAX Networks	WiMAX Networks: Techno-Economic Vision & Challenges (Springer)
Patent	July 2010	Managing Link Layer Resources for Media Independent Handover	European Patent Office

Table 1-6: Publications on optimized fusion of heterogeneous wireless ANs (part II)

Type	Date	Title	Target
Conference	Aug 2010	Evaluation and Comparison of Signaling Protocol Alternatives for the Ultra Flat Architecture	ICSNC
Conference	Sept 2010	Heterogeneous Mobility in Next Generation Devices: An Android-based Case Study	MobiMedia
Conference	Nov 2010	An Experimental Testbed of Optimized Inter-Technology Handovers	CRC
Journal	Mar 2011	Evaluation of Two Integrated Signaling Schemes for the Ultra Flat Architecture using SIP, IEEE 802.21 and HIP/PMIP Protocols	International Journal of Computer and Telecommunications Networking, Computer Networks, Special Issue on Network Convergence (Elsevier)
Journal	April 2011	Enabling Heterogeneous Mobility in Android Devices	ACM Springer Mobile Networks and Applications (MONET) Journal, Special Issue on Mobile Networks and Management (Springer)
Conference	May 2011	Media Independent Handover Management in Heterogeneous Access Networks – An Empirical Evaluation	IEEE VTC
Workshop	June 2011	A Hybrid MIPv6 and PMIPv6 Distributed Mobility Management: the MEDIEVAL approach	IEEE MediaWin (collocated with IEEE ISCC)
Conference	June 2011	An Architecture for Optimized Inter-Technology Handovers: Experimental Study	IEEE ICC
Pre-product	Aug 2011	MyMove – Seamless Mobility Platform for 3G and Wi-Fi Access Networks	PTIN
Product	Sept 2011	MyConnect – Connection Manager for Heterogeneous Access Networks	PTIN
Journal	Dec 2011	MyConnect - Solução PTIN para Gestão de Conectividade em Redes de Acesso Heterogéneas	PTIN – Saber & Fazer
Journal	Dec 2011	Always Best Connected - Resultados e Desafios de Implementação na Rede de um Operador	PTIN – Saber & Fazer

Further details about the proposed mobility architecture for heterogeneous wireless ANs are provided in chapter 6.

1.4.4. Context-aware Media Independent Handovers

Finally, to complete the work within the framework of this Thesis, the final major contribution is to **extend the handover decision-making processes in heterogeneous access environments through the integration of context information** from both the network elements and the end-user.

The **context information is stored on the IEEE 802.21 Information Server (IS)**, being therefore named as CIS. To **transport the context information** from the context providers towards the IEEE 802.21 CIS, an

extension to the IEEE 802.21 Media Independent Information Service (MIIS) messages and primitives is proposed.

Finally, taking into account the integration of context information with the mobility procedures, a **proposal is made to optimize the handover preparation phase**, aiming to minimize the total handover latency.

Table 1-7 describes the Thesis contributions in this research area.

Table 1-7: Publications on context-aware MIHs

Type	Date	Title	Target
Patent	Dec 2010	Mechanism to Optimize Mobility Processes in Heterogeneous Access Networks	European Patent Office
Conference	June 2010	Dynamic Media Information Server	IEEE ISCC
Journal	Mar 2011	Context-aware Media Independent Information Server for Optimized Seamless Handover Procedures	International Journal of Computer and Telecommunications Networking, Computer Networks, Special Issue on Network Convergence (Elsevier)

Further details about the proposed context-aware MIHs are discussed in chapter 7.

1.5. Structure

The present Thesis is organized as follows:

- Chapter 2 provides an overview of the reference technologies used in the scope of this thesis, more precisely the WiMAX, Wi-Fi, UMTS, HSPA and LTE wireless access technologies are presented, as well as the IEEE 802.21 framework and the QoS and mobility management procedures currently defined in the literature. Furthermore, this chapter also depicts the related work available in the scientific literature for each one of the aforementioned objectives;
- Chapter 3 presents several WiMAX and LTE based BWA scenarios ranging from fixed to mobile solutions, from backhaul for coverage extension to last mile connectivity, from business to residential and from urban to rural and impervious areas. In terms of applications, besides normal communication between users, two main types are described, namely, medical and environmental monitoring applications;
- Chapter 4 describes a complete all-IP end-to-end WiMAX network environment. The main focus of the designed architecture is related with QoS provisioning comprising resource management, resource request signaling and reservation as well as resource control, for which detailed architectural design is presented. The WiMAX cross-layer framework is thoroughly described, focusing on its functionalities, as well as on its internal services and correspondent interactions. Performance measurements obtained from a real network prototype are also provided;
- Chapter 5 provides an overview of the designed QoS and mobility architecture for WiMAX, as well as a detailed description of the required mobility extensions for the WiMAX cross-layer framework. Moreover, the most suitable transport protocol to carry the IEEE 802.21 primitives is also studied and a proposal based on the NSIS framework is described to address this issue. Performance measurements obtained from a real network prototype are also provided;
- Chapter 6 presents an inter-technology mobility architecture based on IEEE 802.21, discussing alternative implementations for the IEEE 802.21 Point of Attachment (PoA) and Point of Service (PoS) entities, as well as the proposed IEEE 802.21 radio resource management primitives. Additionally, this chapter also addresses the integration between the IEEE 802.21 primitives and the WiMAX, Wi-Fi and 3GPP RATs, providing a complete inter-technology seamless handover

procedure. To finalize, a large-scale performance evaluation is made through simulations, as well as an evaluation in a real network prototype;

- Chapter 7 extends the heterogeneous seamless mobility architecture with context-aware information to optimize handover decisions. It is also presented the inter-technology context-aware mobility architecture performance measurements obtained through a network prototype integrated in a real operator scenario. Simulations are also made to assess the CIS performance in environments with a large number of users;
- Chapter 8 presents the conclusions of this thesis and the envisaged future work.

2. Background & Related Work

This chapter provides the required background information about the WiMAX, Wi-Fi, UMTS/HSPA and LTE radio access technologies (section 2.1), as well as a short description of the Media Independent Handover (MIH) framework defined by IEEE 802.21 (section 2.2). Finally, section 2.3 provides the related work for each one of the research challenges identified in chapter 1.

2.1. Broadband Wireless Access Technologies

This section presents an overview of the Broadband Wireless Access (BWA) technologies that are used in the scope of this thesis, namely WiMAX, Wi-Fi, UMTS/HSPA and LTE. The description is focused on architectural aspects, Quality of Service (QoS) provisioning mechanisms and existing horizontal handover mechanisms.

2.1.1. IEEE 802.16 / WiMAX

IEEE 802.16 defines a BWA technology for metropolitan area networks (MANs), supporting both fixed and mobile terminals, as defined in the IEEE 802.16d [19] and IEEE 802.16e [20] standards, respectively. Point-to-multipoint (PtMP) is the basic mode of operation of IEEE 802.16 technology and is composed by a Base Station (BS) connected to the Core Network (CN) and in contact with fixed wireless Subscriber Stations (SSs) and/or Mobile Nodes (MNs). Figure 2-1 illustrates the IEEE 802.16 topologies.

Although IEEE 802.16e can deliver high end-user data rates, ITU IMT-Advanced [13], which will supersede ITU IMT-2000, states that the next generation wireless technologies, to be deployed by 2015, must provide much greater data rates while allowing for high user mobility and delivering a wide range of services to users. More specifically, ITU IMT-Advanced dictates that data rates may exceed 100 Mbps in high mobility scenarios and 1 Gbps in low mobility scenarios. Recently, the IEEE 802.16 working group presented a new standard titled “Air Interface for Fixed and Mobile Broadband Wireless Access Systems – Advanced Air Interface” [21], also known as IEEE 802.16m, which is an evolution of IEEE 802.16e standard. An important consideration is that IEEE 802.16m will be backwards compatible with IEEE 802.16e, enabling both standards to use the same BS.

Before we analyze Figure 2-1, it is important to refer that the IEEE 802.16 technology is totally connection-oriented. Therefore, all tasks are based on a connection and no packets are allowed to traverse the wireless link without a specific connection allocated. A connection is, by definition, a unidirectional mapping between the BS and the SS MAC layers for the purpose of transporting a Service Flow (SF) traffic. To uniquely identify a connection, a 16-bit Connection Identifier (CID) is used.

Referring to Figure 2-1, all SSs/MNs within the same frequency channel receive the same transmission from the BS. The BS sends packets to the SSs/MNs multiplexing data in a Time Division Multiplex (TDM) fashion. Since the BS, in a specific frequency channel, is the only transmitter in the downlink direction, it does not have to coordinate with other BSs to transmit in the downlink. Therefore, the downlink subframe is broadcasted to all the SSs/MNs. Each SS/MN reads the MAC Protocol Data Units (PDU) inside the downlink subframe and checks if the CID refers to a connection destined for it. If the CID refers to another SS/MN, the SS/MN discards that specific MAC PDU. On the other hand, the uplink channel is shared between the several SSs/MNs connected to the BS in an on-demand basis, using Time Division Multiple Access (TDMA). For this purpose, there is a dedicated uplink scheduling service associated to each flow. A set of uplink scheduling services are available which determine the rights to transmit in the uplink to each SS/MN, giving the SSs/MNs continuing rights to transmit, or the right to transmit may be granted by the BS after the receipt of a bandwidth request message from the user. Also associated with the uplink scheduling services are polling and contention procedures.

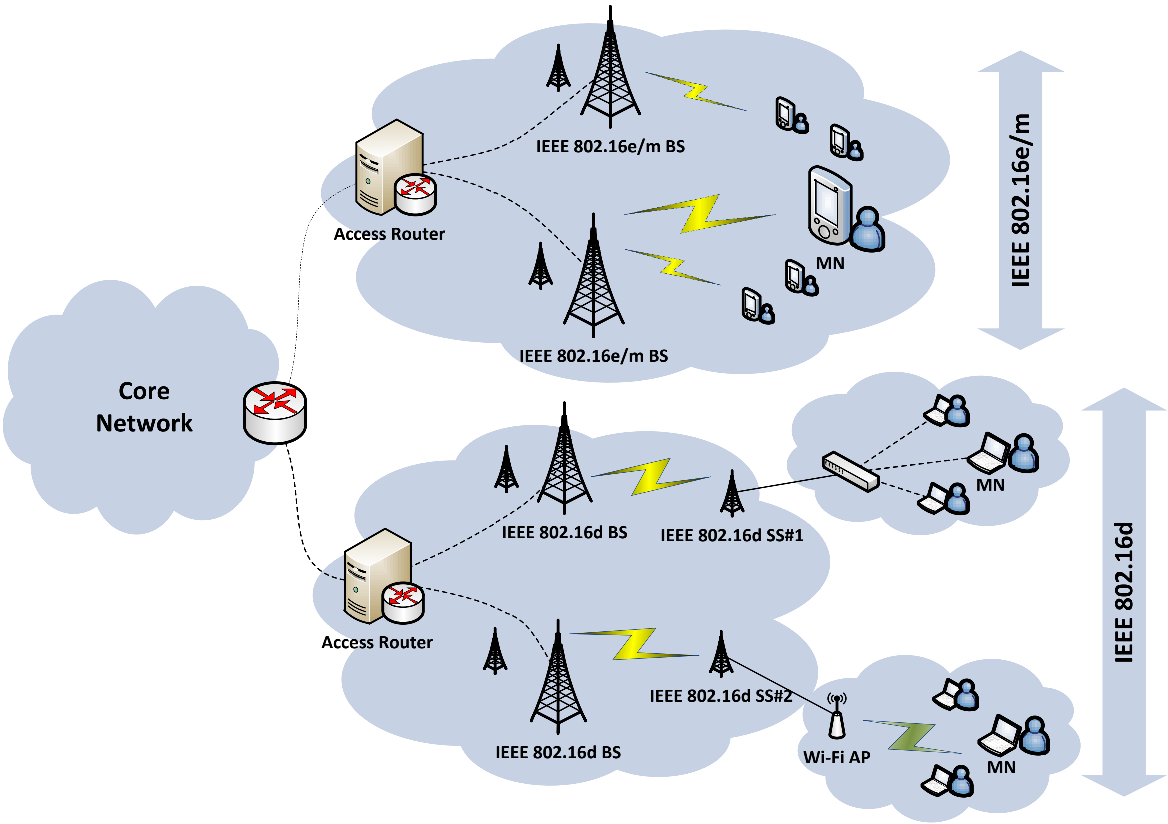

Figure 2-1: IEEE 802.16 topologies

Besides the PtMP topology, the mesh topology is also specified in the IEEE 802.16 standard. While in PtMP mode traffic only occurs between the BS and the SSs/MNs, in the mesh topology traffic can occur directly between SSs/MNs.

As illustrated in Figure 2-2, the MAC layer is divided in three sublayers, namely, the Service Specific Convergence Sublayer (CS), the MAC Common Part Sublayer (CPS) and the Security Sublayer.

The CS is the first sublayer of the MAC layer; it accepts higher layer MAC Service Data Units (SDUs) through the CS Service Access Point (SAP) and classifies them to the appropriate connection. The classifier is based on a set of matching criteria applied to each individual packet, consisting of specific protocol fields (e.g. IPv4/v6, Ethernet, Virtual Local Area Network – VLAN, Transmission Control Protocol – TCP and User Datagram Protocol – UDP ports), a classifier priority and a reference to a CID. Downlink classification is made at the BS whereas uplink classifiers are located in the SS/MN. When the classification process concludes, packets are delivered to the MAC CPS through the MAC SAP.

The MAC CPS is responsible for the core MAC functions, such as system access, bandwidth request and allocation mechanisms, connection establishment, contention resolution, and QoS management. QoS is catered for by associating each packet traversing the air interface with a SF, as identified by the CID. According to IEEE 802.16, a SF is a unidirectional flow of packets with a specific set of QoS parameters, such as latency, jitter, throughput and scheduling service. The scheduling service allows the IEEE 802.16 system to define transmission ordering and scheduling on the air interface, as well as how the SS/MN requests uplink bandwidth allocations.

The Security Sublayer is the third and last sublayer from the MAC layer. This sublayer provides authentication and data encryption functions.

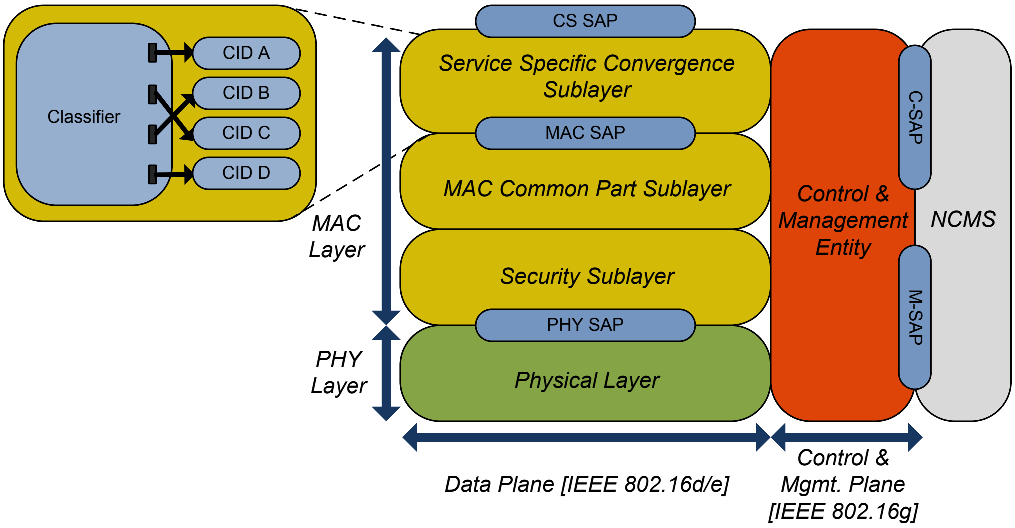

Figure 2-2: IEEE 802.16 reference model (data, control and management planes)

The PHY layer defined by the IEEE 802.16 standard supports both frequency and time division duplex techniques. Adaptive burst profiling, including the modulation and coding schemes can be individually adjusted to each SS/MN on a frame-by-frame basis. Several modulation techniques, such as Quadrature Phase Shift Keying (QPSK), 16-state Quadrature Amplitude Modulation (16-QAM) and 64-QAM, are supported, allowing the formation of varying robustness and efficient burst profiles.

When the Frequency Division Duplex (FDD) technique is used, two separate frequency channels are allocated: one uplink channel and one downlink channel. As a consequence of using the FDD technique, full-duplex SSs (can transmit and receive simultaneously) and half-duplex SSs (cannot transmit and receive simultaneously) are supported. The frames duration (uplink and downlink) is fixed, allowing the utilization of different modulation techniques.

When the Time Division Duplex (TDD) duplex technique is used, the uplink and the downlink use the same frequency channel. In this case, the uplink and the downlink transmissions must occur in different periods of time, sharing the same frequency channel. As a consequence of using this duplex technique, the SSs work in half-duplex. As in the FDD case, the frame has a fixed duration. However, this frame is divided in two subframes. One subframe is used for the uplink transmission and the other subframe is used for the downlink transmission. Physical Slot (PS) is the unit used to divide the TDD frame. This duplex technique is adaptive because the bandwidth allocated to the downlink and to the uplink can vary depending on the needs.

The IEEE 802.16 PHY layer supports two different frequency bands:

- 10 – 66 GHz licensed bands (*WirelessMAN-SC*);
- 2 – 11 GHz licensed bands (*WirelessMAN-SCa*, *WirelessMAN-OFDM*, *WirelessMAN-OFDMA*).

The 10 – 66 GHz licensed bands provide a physical environment in which a Line Of Sight (LOS) environment is required. The channels bandwidth used in this physical environment are usually large (25 or 28 MHz). The 10 – 66 GHz licensed bands provide transmission rates of 120 Mbps, being a good option for

PtMP access in LOS environments. This single-carrier modulation air interface is known as *WirelessMAN-SC* air interface.

The 2 – 11 GHz licensed bands provide a physical environment where LOS environment is not mandatory. By supporting Non Line Of Sight (NLOS) scenarios, it requires additional PHY functionalities. It provides lower transmission rates (75 Mbps) when compared to the 10 – 66 GHz, but it does not require a LOS environment. Three air interfaces are defined in this frequency band:

- *WirelessMAN-SCa*: single carrier air interface;
- *WirelessMAN-OFDM*: multi-carrier air interface using Orthogonal Frequency Division Multiplexing (OFDM) with 256 carriers;
- *WirelessMAN-OFDMA*: multi-carrier air interface using Orthogonal Frequency Division Multiple Access (OFDMA) with 2048 carriers.

Since the IEEE 802.16 entities are part of a larger network environment, it is necessary to define control and management communication mechanisms with the higher layers. The IEEE 802.16g standard [41] has been defined to efficiently integrate the IEEE 802.16 entities with the higher layer control and management functionalities (see right-hand side of Figure 2-2). In particular, IEEE 802.16g specifies the Network Control and Management System (NCMS) abstraction, which represents the higher layers entities (e.g. QoS and/or mobility management functions) that interoperate with the IEEE 802.16 system.

Furthermore, the Control Service Access Point (C-SAP) and the Management Service Access Point (M-SAP) establish communication between an IEEE 802.16-based system and NCMS entity(ies) for control and management purposes, respectively. The M-SAP is used for less time-sensitive management plane primitives, such as system configuration, monitoring statistics, notifications, triggers and multi-mode interface management. Besides, the C-SAP is used for more time sensitive control plane primitives, including handover, mobility management, security context management, radio resources management, subscriber and session management, and Media Independent Handover Function (MIHF) services.

IEEE 802.16 specifies the air interface, including the MAC and the PHY layers. Nevertheless, it does not deal with the IP-level functionalities. The standardization of the IEEE 802.16 IP framework is part of the WiMAX Forum. For this reason, the IEEE 802.16d and IEEE 802.16e systems are also known as fixed and mobile WiMAX, respectively. Besides defining an IP framework to support IEEE 802.16, the WiMAX Forum also aims to ensure full interoperability between BSs and SSs/MNs from different WiMAX vendors.

The WiMAX Forum introduced an architecture based on IEEE 802.16 by defining the Network Reference Model (NRM) [42]. The NRM is a logical representation of the WiMAX network architecture, based on a set of functional entities and standardized interfaces, known as Reference Points (RPs). The WiMAX NRM defines three functional entities, namely, the Connectivity Service Network (CSN), the Access Service Network (ASN) and the MN. The MN is also referred to as the terminal equipment, and is responsible for establishing radio connectivity with the BS. The ASN provides the connectivity between the MN and the IP backbone. The ASN is generally composed of several BSs connected to one or several ASN-Gateways (ASN-GW). The ASN-GW is the gateway for the ASN, aggregating all BSs' information towards the CSN. The ASN is responsible for a set of important functionalities to provide radio connectivity to WiMAX subscribers, such as network discovery and selection, radio resource management, multicast and broadcast control, intra-ASN mobility, accounting, admission control, and QoS. Furthermore, the ASN also performs relay functions to the CSN for IP connectivity establishment. Finally, the CSN complements the ASN by providing IP connectivity-related services. For example, the CSN operates Dynamic Host Configuration Protocol (DHCP), Domain Name Service (DNS) and Authentication, Authorization, and Accounting (AAA) servers, and oversees mobility management procedures.

Since IEEE 802.16 is a connection-oriented technology, all data transfers require the prior establishment of dedicated connections between the BS and the SS/MN. A connection, which is identified by a 16-bit CID, is a unidirectional mapping between the BS and the SS/MN MAC layer for transporting the traffic of the corresponding SF. During the SS/MN initialization process, three pairs of management connections (basic, primary and secondary) are established between the BS and the SS/MN, reflecting distinct QoS levels. The basic connection is used to transfer short, time-critical MAC management messages. The primary management connection transports longer, more delay-tolerant management messages. The secondary management connection is used to transfer delay-tolerant, standard-based management messages such as DHCP, Trivial File Transfer Protocol (TFTP) and Simple Network Management Protocol (SNMP). Moreover, a broadcast connection is configured by default to transmit MAC management messages to all receivers. Besides the aforementioned management connections, a multicast polling connection is also established so the SS/MN joins multicast polling groups and requests additional bandwidth. Finally, to satisfy the contracted services, transport connections are allocated to convey data packets in the air interface.

A SF is partially characterized by the following attributes:

- *Service Flow ID*: an SFID is assigned to all existing SFs. The SFID serves as the principal identifier in the SS/MN and the BS for the SF. A SF has at least an SFID and an associated direction;
- *Connection ID*: mapping to an SFID exists only when the connection has an admitted SF;
- *ProvisionedQoSParamSet*: a QoS parameter set provisioned via means outside of the scope of IEEE 802.16 standard, such as the Network Management System (NMS);
- *AdmittedQoSParamSet*: defines a set of QoS parameters for which the BS (and possibly the SS/MN) is reserving resources. The principal resource to be reserved is bandwidth, but this also includes any other memory or time-based resource required to subsequently activate the flow;
- *ActiveQoSParamSet*: defines set of QoS parameters defining the service actually being provided to the SF. Only an Active SF may forward packets;
- *Authorization Module*: a logical function within the BS that approves or denies every change to QoS parameters and classifiers associated with a SF. As such it defines an "envelope" that limits the possible values of the *AdmittedQoSParamSet* and *ActiveQoSParamSet*.

A SF may have one of the following statuses:

- *Provisioned*: this type of SF is known via provisioning by, for example, the NMS. Its *AdmittedQoSParamSet* and *ActiveQoSParamSet* are both null;
- *Admitted*: this type of SF has resources reserved by the BS for its *AdmittedQoSParamSet*, but these parameters are not active (its *ActiveQoSParamSet* is null). Admitted SFs may have been provisioned or may have been signaled by some other mechanism;
- *Active*: this type of SF has resources committed by the BS for its *ActiveQoSParamSet*, (e.g., is actively sending maps containing unsolicited grants for a UGS-based SF). Its *ActiveQoSParamSet* is non-null.

Five scheduling services, associated with each connection during the system setup, are defined to meet different QoS needs: (i) Unsolicited Grant Service (UGS); (ii) extended real-time Polling Service (ertPS); (iii) real-time Polling Service (rtPS); (iv) non-real-time Polling Service (nrtPS) and (v) Best Effort (BE). Table 2-1 describes each one of the mentioned scheduling services.

A set of QoS parameters can be identified by a Service Class (SC). This concept is defined in IEEE 802.16d and has two main purposes:

- First, a SS/MN can be configured only with the SC name while the real implementation of the SC parameters' values can be configured at the BS;
- Second, it allows applications to request a SF by its SC name. IEEE 802.16e standard provides global SCs to define a common set of SC names and relative parameters' values in order to facilitate operations across a distributed topology.

An admitted or an active SF is associated with a 16-bit CID that identifies the MAC transport connection. The mapping between packets and their transport connections is done through a classifier rule. The IEEE 802.16d/e standards define several types of classifiers: IPv4, IPv6, Ethernet, 802.1Q VLAN and combinations of them.

SFs activations, modifications or deletions can be initiated from both the BS and/or by the SS/MN, with a three-way handshake. For SF creation, three MAC management messages are used. First, a *Dynamic Service Addition Request* (*DSA-REQ)* message is sent by the BS to the SS/MN to request the allocation of a new SF, including the QoS parameters. Then, a *DSA-RSP* message is sent by the SS/MN as a response, indicating whether the requested QoS parameters are supported. Finally an *Acknowledgment (DSA-ACK)* is sent by the BS to the SS/MN to confirm and acknowledge the reception of the *DSA-RSP*. When dynamic SF modification is required, a similar set of messages is used: *Dynamic Service Change Request (DSC-REQ)*, *Dynamic Service Change Response (DSC-RSP)* and *Dynamic Service Change Acknowledgment (DSC-ACK)*.

Finally, the groups of messages used to delete service flows are: *Dynamic Service Deletion Request (DSD-REQ)*, *Dynamic Service Deletion Response (DSD-RSP)* and *Dynamic Service Deletion Acknowledgment (DSD-ACK)*. The MAC management messages used for the SF establishment process are illustrated in Figure 4-11.

In order to trigger QoS procedures in an IEEE 802.16 system, the NCMS provides the Service Flow Management (SFM) service. The SFM service is composed by a set of primitives for supporting QoS management between the BS and SS/MN. The interaction between the NCMS and the IEEE 802.16 QoS system is done through the C-SAP. The SFM service is based on a two-way handshake based on the following two primitives. First, a *Control Service Flow Management Request (C-SFM-REQ)* primitive is sent by the NCMS to the IEEE 802.16 MAC system to start a SF management procedure, such as SF creation. Effectively a *C-SFM-REQ* triggers the *DSA-REQ* MAC message, described earlier, or a modification (triggers a *DSC-REQ* MAC message), or deletion (triggers a *DSD-REQ* MAC message). Second, a *Control Service Flow Management Response (C-SFM-RSP)* primitive is sent back as a response to the requested SF management procedure (based on a *DSA-RSP*, *DSC-RSP* or *DSD-RSP* MAC messages, respectively).

Table 2-1: IEEE 802.16 scheduling services and QoS parameters

WiMAX Scheduling Service	Target Services	QoS Parameters
UGS	Support real-time SFs that generate fixed size data packets on a periodic basis, such as VoIP;	Maximum Sustained Traffic Rate (equal to the Minimum Reserved Traffic Rate) Maximum Latency Tolerated Jitter Request/Transmission Policy
rtPS	Support real-time SFs that generate variable size data packets on a periodic basis, such as MPEG video or streaming video;	Maximum Sustained Traffic Rate Minimum Reserved Traffic Rate Maximum Latency Request/Transmission Policy
ertPS	Support real-time SFs that generate variable size data packets on a periodic basis, such as VoIP with silent suppression. Instead of providing fixed allocations such as UGS, ertPS provides dynamic allocations;	Maximum Sustained Traffic Rate Minimum Reserved Traffic Rate Maximum Latency Request/Transmission Policy
nrtPS	Support non-real-time SFs that require variable size data grants on a regular (but not strictly periodic) basis, such as high bandwidth FTP;	Maximum Sustained Traffic Rate Minimum Reserved Traffic Rate Traffic Priority Request/Transmission Policy
BE	Support SFs with no throughput or delay guarantees.	Maximum Sustained Traffic Rate Traffic Priority Request/Transmission Policy

IEEE 802.16e standard defines a framework for supporting mobility. Three handover methods are supported in IEEE 802.16e, but only one is mandatory. The mandatory handover method is called Hard Handover (HHO), or otherwise known as *break-before-make* handover and it is the only handover type required to be implemented by IEEE 802.16e. HHO implies that there may be an abrupt transfer of connection from one BS to another. In this case the serving network link is broken before the handover execution is triggered and the target link is established. The two optional handover methods defined in IEEE 802.16e, which both fall under the category of *make-before-break* or Soft Handovers (SHO), are Fast Base Station Switching (FBSS) and Macro Diversity Handover (MDHO). In the FBSS handover case, the MN is able to rapidly switch between several BSs without completing the entire network entry procedure. In the MDHO mode, the MN has simultaneous communication links with several BSs, enabling a fast handover to occur with minimum traffic degradation. Although the SHO methods provide continuous connectivity for

the MN, they are much more complex and require backbone communication between the serving and the target IEEE 802.16e links.

Both mobile (MIHO) and network initiated handovers (NIHO) are supported in IEEE 802.16e. For the former case, the MN is responsible to trigger the handover initiation process, whereas for the network initiated handover scenario, the serving BS is in charge of triggering the mobility procedures. IEEE 802.16e only defines the air interface procedures, including the MAC management messages that are exchanged between the BS and the MN. All the communication procedures in the backbone network are not covered by IEEE 802.16e itself. To overcome this gap, the WiMAX Forum has specified a network protocol to establish the communication in the backbone network between the serving, candidate and target BSs, as well as between the BSs and the ASN-GWs.

Four MAC management messages are defined in IEEE 802.16e for integrating mobility support, including both MIHO and NIHO: *Mobility Mobile Station/Base Station Handover Request (MOB-MSHO-REQ and/or MOB-BSHO-REQ)*, *Mobility Base Station Handover Response (MOB-BSHO-RSP)* and *Mobility Handover Indication (MOB-HO-IND)*.

For a MIHO, the MN starts by sending a *MOB-MSHO-REQ* message to the serving BS with a list of the possible target BSs. The serving BS contacts the target BSs over the backbone network to check whether they have enough resources to support the requested QoS parameters for the handover. Note that the backbone communication between the serving and the target BSs is left undefined by IEEE 802.16e. After receiving the response from the target BSs, the serving BS summarizes the results obtained from the target BSs and informs the MN using the *MOB-BSHO-RSP* MAC management message. The *MOB-BSHO-RSP* message includes a recommended list of the target BSs that can effectively support the MN handover. Finally, the MN selects the target BS and notifies the serving BS using the *MOB-HO-IND* message.

With respect to the NIHO scenario, the serving BS informs the MN that it is going to be switched to another BS using the *MOB-BSHO-REQ* message. Thereafter, if the MN is able to make the handover to one of the recommended BSs, it replies with the *MOB-HO-IND* message, indicating its commitment to the handover.

For triggering the handover messages in the IEEE 802.16e system, the NCMS, defined by IEEE 802.16g, provides a set of control primitives for the handover process, through the C-SAP, that support the handover procedures between the BS and the MN. The handover control primitives are based on a three-way handshake. First, a *Control Handover Request (C-HO-REQ)* primitive is used by the IEEE 802.16 system or NCMS to start a MIHO (triggering a *MOB-MSHO-REQ* MAC message) or a NIHO (triggering a *MOB-BSHO-REQ* MAC message). Thereafter a *Control Handover Response (C-HO-RSP)* primitive is used by the IEEE 802.16 system or by the NCMS to respond to the handover request (triggering the *MOB-BSHO-RSP* MAC message). Third, the *Control Handover Indication (C-HO-IND)* primitive is used to explicitly notify the handover execution (triggered by the *MOB-HO-IND*), cancellation or completion.

As discussed earlier, IEEE 802.16e specifies the communication between the BS and the MN using the MAC management messages. On the other hand, IEEE 802.16g specifies the control primitives to manage the handovers using a set of mobility management primitives. Nevertheless, neither IEEE 802.16e nor IEEE 802.16g specify the communication between the serving and the target BSs in the backbone network. This communication link is very important to transfer the context information between the serving and the target BSs. To fill this gap, the WiMAX Forum has specified a network protocol that establishes communication between the serving and the target BSs. Three messages have been defined: (i) a *Handover Request* (*HO-REQ*) message is sent by the serving BS to inform the target BSs that the MN is requesting a handover (includes the list of QoS parameters required by the MN SFs); (ii) a *Handover Response* (*HO-RSP*) message is sent by the target BSs back to the serving BS announcing whether the required QoS parameters are available; and (iii) a *Handover Confirmation* (*HO-CNF*) message is sent by the serving BS to alert the chosen target BS for the MN handover.

2.1.2. 3GPP UMTS/HSPA

Mobile communications, in previous years, was one of the segments that have grown more rapidly; this was supported by the increase of the number of subscribers. Since its commercial launch in 1992, the Global System for Mobile Communication (GSM) emerged as a European standard to the mobile communication, providing services through almost 200 networks in more than 100 countries worldwide.

Nowadays, thanks to cellular systems, users are reachable almost everywhere. The Universal Mobile Telecommunications System (UMTS) [14] along with High-Speed Packet Access (HSPA) [15] are the most recent technologies in cellular systems, which appeared to overcome the limitations of GSM and General Packet Radio Service (GPRS).

UMTS is the 3rd generation (3G) network more commonly widespread and accepted. It is an evolution from 2nd generation GSM network, but uses W-CDMA (Wideband Code Division Multiple Access) which is a wideband spread spectrum that utilizes the direct sequence Code Division Multiple Access (CDMA) as access method. QoS on UMTS networks is controlled and managed by signaling and scheduling mechanisms that perform differentiation per flow. It also includes access control algorithms and may perform resource reservation.

To increase the network performance, several enhancements were achieved. High Speed Downlink Packet Access (HSDPA) facilitates the transmission of large files to mobile devices such as email attachments. It allows speeds of 1.8, 3.6, 7.2 and 14.4 Mbps download rate. High Speed Uplink Packet Access (HSUPA) is an enhancement to increase the upload speed from the mobile device up to a maximum of 5.7Mbps.

UMTS architecture, illustrated in Figure 2-3, is the evolution of the GSM and GPRS networks.

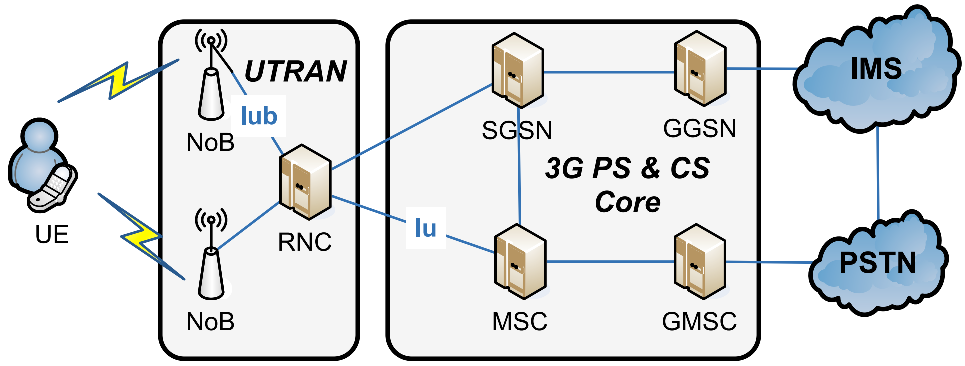

Figure 2-3: UMTS architecture

The UMTS Terrestrial Radio Access Network (UTRAN) is the network that contains the procedures and protocols used to transmit data from the User Equipment (UE) to the Internet and vice versa. UTRAN consists of one or more Radio Network Subsystem (RNS). The RNS consists of one Radio Network Controller (RNC) and multiple access antennas, also known as NodeBs (NB).

- *NB*: In UMTS terminology the radio Access Points (APs) are named Node B, contrary to the Base Transceiver Station (BTS) in GSM and GPRS systems. The main task of this network element is the conversion of data to and from the UE including Forward Error Correction (FEC). Each NB is directly connected to a RNC;
- *RNC*: is responsible for controlling a set of NBs. It carries out radio resource management and some of the mobility management functions. Moreover, it is responsible for the following functions: channel allocation, power control settings, handover control, macro diversity, ciphering, segmentation and reassembly, broadcasting signaling, and open loop power control.

The CN is logically divided in two domains: the Circuit Switched Domain (CSD) for services based on channel-switched and the Packet Switched Domain (PSD) for services based on packet-switched. All the core devices are integrated in CSD or/and in PSD. The Mobile Switching Centre (MSC) and the Gateway MSC (GMSC) belong to the CSD, whereas the Serving GPRS Support Node (SGSN) and the Gateway GPRS Support Node (GGSN) belong to the PSD. All the components from the UMTS architecture were designed to facilitate the transition between the 2G systems to an IP based network.

- *MSC*: provides UMTS 3G wireless telephony switching services and controls calls between telephone and data systems. It is a switch that serves the UE in its current location for circuit switched (CS) services;

- *GMSC*: MSC server that controls the connections to other networks; serves the UMTS network at the point where it is connected to the external CS network;
- *Media Gateway (MGW)*: termination point of Public Switch Telephone Network / Public Land Mobile Network (PSTN/PLMN) for a defined network and interfaces UTRAN with the CN. The MSC and GMSC handle control functionality, but user data goes through the MGW;
- *SGSN*: covers functions similar to the MSC for packet data. It is responsible for tunneling IP packets toward the GGSN (uplink) and untunneling GPRS Tunneling Protocol (GTP) packets from the GGSN (downlink);
- *GGSN*: connects the packet switched network to external networks. It converts the packets coming from the SGSN into the appropriate Packet Data Protocol (PDP) format and forwards them out on the corresponding packet data network;
- *Home Location Register (HLR)*: responsible to act as a database in charge of the mobile subscribers;
- *Visitor Location Register (VLR)***:** when a UE roams in an MSC area, the control is made by the VLR. The MSC in charge of the roaming area notices this registration and transfers to the VLR the identity of the new location area.

An end-to-end service may have a certain QoS which is provided to the user of a network service. From a QoS point of view, the UMTS relies on a layered bearer service architecture with clearly defined characteristics and functionalities. A bearer service includes all aspects to enable the provision of a contracted QoS, defining individual QoS parameters such as traffic type, bit rates and/or error ratio.

The UMTS QoS architecture defines four different QoS classes, also referred to as traffic classes. The differentiation is mainly done considering the delay sensitiveness of the information to be carried. Table 2-2 illustrates the QoS classes for UMTS.

Table 2-2: UMTS QoS classes

Traffic Class	Description	Example Application
Conversational	Preserve time relation (variation) between information entities of the stream Conversational pattern (stringent and low delay)	Voice
Streaming	Preserve time relation (variation) between information entities of the stream	Streaming video
Interactive	Request response pattern Preserve payload content	Web browsing
Background	Destination is not expecting the data within a certain time Preserve payload content	E-mail

Wireless networks are by definition technologies where the end user does not require being physically attached to the network on which it is connected. Moreover, wireless users expect to be able to move, inside certain limits, and still able to be connected. UMTS is designed to allow the handover between micro-cells, regular cells, and different RNC zones. Furthermore, it presents mechanisms to allow user roaming between different providers.

There are three types of handovers within UMTS: hard, soft and softer handover. The first mechanism means that all the old radio links in the UE are removed before the new radio links are established. In the soft handover the radio links are added and removed in a way that the UE always keeps one radio link. Finally, the softer handover derives from the soft handover, but in this mechanism the radio links that are added and removed belong to the same NB.

2.1.3. 3GPP LTE

Besides working on the evolution of the HSPA technology, 3GPP is also introducing and defining an innovative radio access system called LTE. LTE, whose air radio access is called Evolved Universal Terrestrial

Radio Access Network (E-UTRAN) uses OFDMA and supports Multiple Input Multiple Output (MIMO) antenna technology, providing higher data rates, improved spectral efficiency and reduced latency. In parallel, to support the E-UTRAN air interface, 3GPP is defining a new packet core network – the Evolved Packet Core (EPC) architecture – through the System Architecture Evolution (SAE). The combination of LTE and SAE provides the 3GPP vision for the 4G paradigm, an all-IP based architecture, providing higher data rates with seamless mobility support.

The E-UTRAN consists of E-UTRAN NodeB (eNBs), providing the E-UTRAN user plane (Physical – PHY, Medium Access Control – MAC, Radio Link Control – RLC, Packet Data Control Protocol – PDCP) and control plane (Radio Resource Control – RRC) protocol terminations towards the UE. The eNBs are interconnected with each other by means of the X2 interface. The eNBs are also connected by means of the S1 interface to the EPC, more specifically to the Mobility Management Entity (MME) and to the Serving Gateway (S-GW) entities. The S1 interface supports a many-to-many relation between the MMEs/SGWs and eNBs. The E-UTRAN architecture is illustrated in Figure 2-4.

As demonstrated in Figure 2-4, the EPC (also called access Gateway – aGW) is composed by the MME, the S-GW and the Packet Data Network Gateway (PDN-GW).

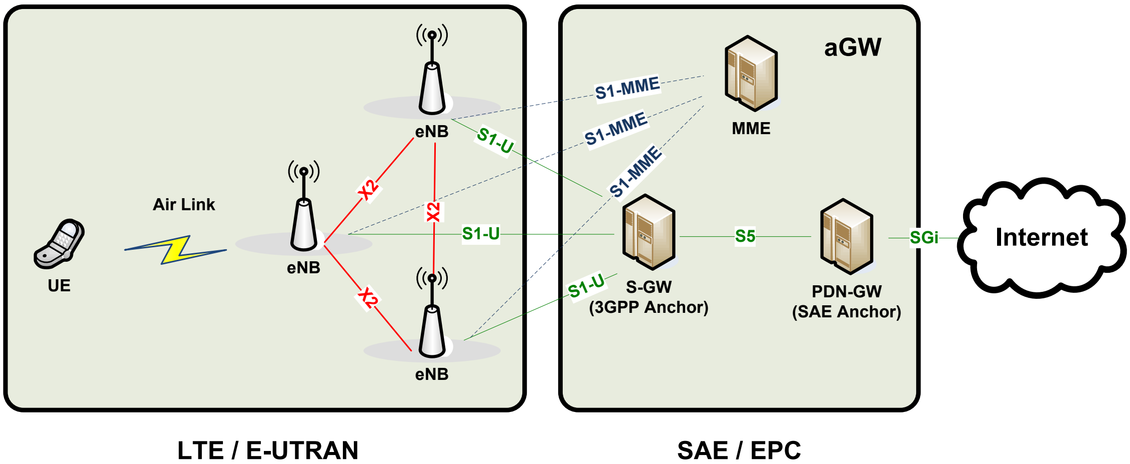

Figure 2-4: LTE architecture

Compared to the current definition of UTRAN, where the functionalities are split across the RNC and the NB, in the E-UTRAN case, all the functionalities are included in the eNB. Merging the RNC and the NB functionalities into a single entity (eNB), reduces the overall latency with fewer hops in the path, and reduces the RNC processing load into multiple eNBs.

The eNB is responsible for the following control plane functions:

- Radio resource management, including radio bearer control, radio admission control, connection mobility control and dynamic allocation of resources to UEs in both uplink and downlink (scheduling);
- Selection of an MME at UE attachment, when no routing to an MME can be determined from the information provided by the UE;
- Scheduling and transmission of paging messages (originated from the MME);
- Scheduling and transmission of broadcast information (originated from the MME).

Regarding the user plane, the eNB is responsible for:

- IP header compression and encryption of user data stream;
- Routing of data towards the S-GW.

The MME is a signaling only entity responsible to manage the UE mobility, UE identities and security parameters. It also performs authentication and authorization functions, Non Access Stratum (NAS) signaling, inter CN node signaling for mobility between 3GPP ANs, idle mode UE reachability (including control and execution of paging retransmission), as well as PDN-GW and S-GW selection during network attachment. Moreover, it also selects the MME for handovers with MME change and the SGSN for handovers to 2G or 3G ANs.

The S-GW is the node that terminates the interface towards the E-UTRAN. Each UE has a specific S-GW dedicated to it. Summarizing, the S-GW is the Local Mobility Anchor (LMA) point for inter-eNB handover and for inter-3GPP mobility. Additionally, it is responsible for lawful interception, packet routing and forwarding, packet marking in the uplink and in the downlink, accounting and charging per UE.

The PDN-GW provides connectivity between the UE and the external packet data networks. The PDN-GW is the mobility anchor point between 3GPP access systems and non-3GPP access systems. It performs per-user based packet filtering (e.g. deep packet inspection), UE IP address allocation, service level charging and policy enforcement.

Figure 2-5 shows the E-UTRAN user and control plane protocol stacks, composed by the PDCP, the RLC, the MAC, the RRC and the NAS.

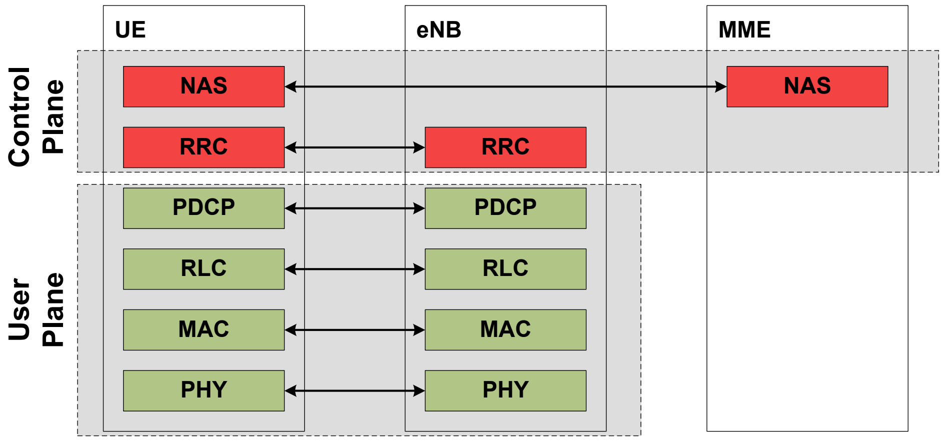

Figure 2-5: User and control planes [17]

The MAC sublayer is responsible for the logical and transport channels mapping, as well as for multiplexing/demultiplexing of RLC PDUs belonging to one or different radio bearers into/from transport blocks delivered to/from the physical layer on transport channels. It also performs traffic volume measurement reporting, error correction through HARQ, priority handling between logical channels of one UE, priority handling between UEs by means of dynamic scheduling, transport format selection and padding.

The RLC sublayer is responsible for upper layer PDUs data transfer, error correction, concatenation of SDUs for the same radio bearer, in-sequence delivery of upper layer PDUs, duplicate detection, protocol error detection/recovery and SDU discard.

Regarding the user plane, the PDCP sublayer is responsible for header compression and decompression (ROHC – Robust Header Compression), transmission of user data (PDCP receives PDCP SDU from the NAS and forwards it to the RLC layer and vice versa), in-sequence delivery of upper layer PDUs at handover, duplicate detection of lower layer SDUs at handover, retransmission of PDCP SDUs at handover and ciphering.

With respect to the control plane, the PDCP sublayer performs ciphering and integrity protection, as well as transmission of control plane data (PDCP receives PDCP SDUs from RRC and forwards it to the RLC layer and vice versa).

The RRC sublayer is responsible for establishing, maintaining and releasing the RRC connections between the UE and E-UTRAN, as well as for security functions including key management. Mobility functions including inter-cell handover, UE cell selection/reselection and context transfer between eNBs are also tasks addressed by the RRC sublayer.

To guarantee services differentiation, and therefore transparent QoS support, specific QoS pipes called Evolver Packet Service (EPS) bearers are established between the UE and the PDN-GW. Each EPS Bearer is associated with a specific QoS profile. The PDN-GW performs packet classification of the incoming packets based on a set of packet matching criteria, redirecting these packets to the appropriated EPS bearer. The eNB then maps the packets to the correspondent radio Bearer. The EPS bearer service layered architecture is depicted in Figure 2-6.

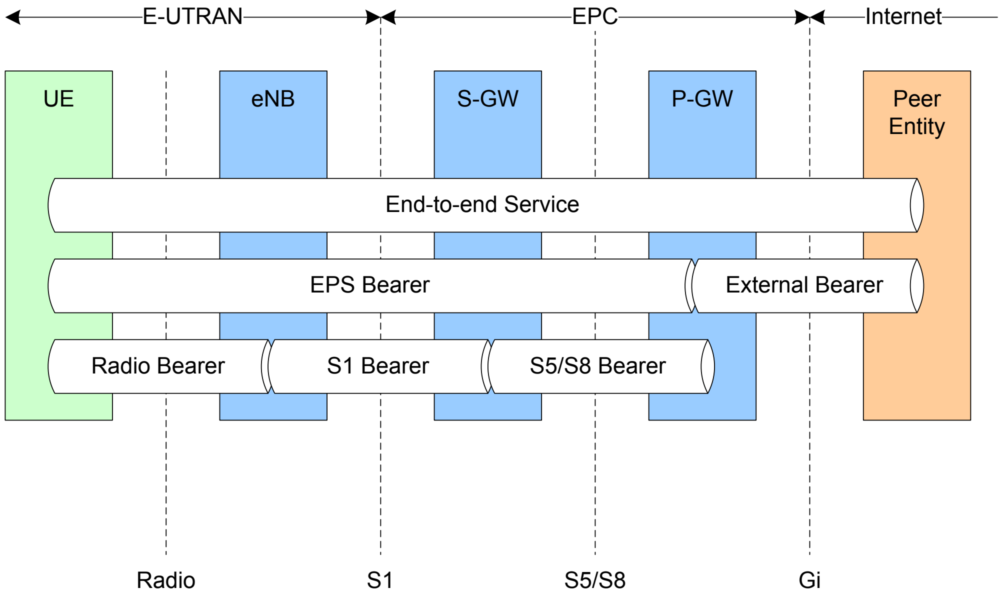

Figure 2-6: EPS bearer service architecture [17]

In the EPS only packet services are supported and the service model is always-on. Among other innovations, the 3GPP architecture also introduced the possibility to directly use non-3GPP accesses to reach the mobile core network and its services. This is done using mobility protocols specified in IETF and can be based on a network-based mobility solution or client-based mobility solution.

2.1.4. IEEE 802.11 / Wi-Fi

Wi-Fi is a globally used wireless networking technology that uses the IEEE 802.11 standard [23]. IEEE 802.11 is a set of standards for Wireless Local Area Networks (WLANs) computer communication, developed by the IEEE standards committee (IEEE 802) in the 5 GHz and 2.4 GHz public spectrum bands. Although the terms Wi-Fi and IEEE 802.11 are commonly used, the Wi-Fi Alliance uses the term "Wi-Fi" to define a slightly different set of overlapping standards.

The basic system of Wi-Fi is very simple. A Wi-Fi network, illustrated in Figure 2-7, consists of APs and mobile devices, that is, PCs, game consoles, cell phones or even music players (the only requirement is to have an IEEE 802.11x interface). The APs are gateway points between the wired network and the wireless network.

Alternatively to this architecture, it is possible to directly connect two mobile devices, forming a point-to-point network (also known as ad-hoc networks). These connections can only be created among devices with the same IEEE 802.11x interfaces, and it is necessary to configure one of the devices as a gateway, which will be responsible for the wireless session. Moreover special routing protocols are required in order for two peers to communicate with each other.

When two or more stations come together to communicate with each other, they form a Basic Service Set (BSS). The minimum BSS consists of two stations. IEEE 802.11 LANs use the BSS as the standard building block.

When BSSs are interconnected the network becomes one with infrastructure. IEEE 802.11 infrastructure has several elements. Two or more BSSs are interconnected using a Distribution System (DS). This concept of DS increases network coverage. Each BSS becomes a component of an extended, larger network. The entry to the DS is accomplished with the use of APs. So, data moves between the BSS and the DS with the help of these APs.

Creating large and complex networks using BSSs and DSs leads us to the next level of hierarchy, the Extended Service Set (ESS). The functionality of the ESS is that the entire network looks like an independent basic service set to the logical link control layer. This means that stations within the ESS can communicate or even move between BSSs transparently to the logical link control layer.

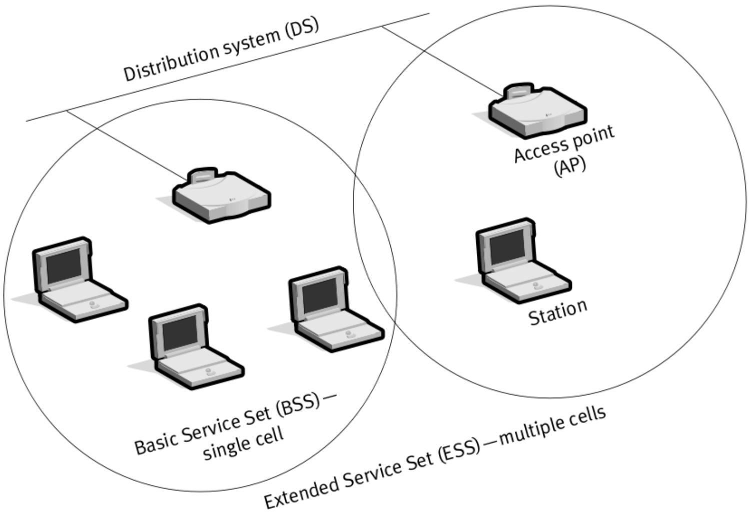

Figure 2-7: Wi-Fi network architecture

Nowadays, there are three available versions of Wi-Fi radios: IEEE 802.11a [43], IEEE 802.11b [44] and IEEE 802.11g [45] specifications. While the first one operates at 5 GHz band, the standards IEEE 802.11b and IEEE 802.11g transmit at 2.4 GHz band. The IEEE 802.11a and IEEE 802.11g standard radios use OFDM, while the IEEE 802.11b uses Complementary Code Keying (CCK). All the IEEE 802.11 specifications use the Ethernet protocol and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) for path sharing. Table 2-3 provides an overview of the main IEEE 802.11 specifications.

Table 2-3: IEEE 802.11 protocols overview

Protocol	Release Data	Frequency	Throughput (Mbps)	Data Rate (Mbps)	Range	
					Indoor (m)	Outdoor (m)
802.11a	*1999*	*5 GHz*	*23*	*54*	35	120
802.11b	*1999*	*2.4 GHz*	*4.3*	*11*	38	140
802.11g	*2003*	*2.4 GHz*	*19*	*54*	38	140
802.11n	*2008*	*5 GHz / 2.4 GHz*	*74*	*248*	70	250

IEEE 802.11n [23] is a proposed amendment which improves upon the previous IEEE 802.11 standards by adding MIMO among other features. It will support up to 248 Mbps data rate and can operate at 5 and 2.4 GHz bands.

IEEE 802.11 divides the used bands into channels, analogously to how radio and TV broadcast bands are carved up but with greater channel width and overlap. As an example, the 2.4 GHz band is divided into 13 channels each of width 22 MHz but spaced only 5 MHz apart. Availability of channels is regulated by country, constrained in part by how each country allocates radio spectrum to various services.

The wireless medium has relatively limited bandwidth and higher packet-error rates with high packet overheads. One of the major shortfalls for the developing applications for Wi-Fi is that it is not possible to allocate a required QoS for a specific application. The issue of QoS on Wi-Fi is of particular importance to some applications. For web-based applications such as web browsing, issues such as small delays in receiving or sending information do not present a major impact. However, this could potentially limit the use of Wi-Fi for delivering traffic for real-time applications such as VoIP telephony and multimedia applications.

Now, with IEEE 802.11e [46], the QoS problem is being addressed. IEEE 802.11e defines priority mechanisms by assigning priority levels to the traffic, based on their QoS requirements, prior to transmission. Furthermore, four different access categories have been defined, each for data traffic of a different priority. Access to the medium is then provided based on the prior established priorities of data traffic. In order to achieve the required functions, the re-developed MAC layer takes on aspects of both the Distributed Coordinated Function (DCF) and Point Coordinated Function (PCF) from the previous MAC layer alternatives and is termed the Hybrid Coordination Function (HCF). In the HCF mechanism, the modified elements of the DCF are termed the Enhanced Distributed Channel Access (EDCA), while the elements of the PCF are termed the HCF Controlled Channel Access (HCCA).

EDCA contention access is an extension to DCF and provides prioritized access to the wireless medium. The EDCA channel-access mechanism defines four AC based on the IEEE 802.1D [47] standard to provide priorities. Each AC has its own transmit queue. EDCA introduces a new class of inter-frame space called Arbitration Inter Frame Space (AIFS). This is chosen such that the higher the priority of the message, the shorter the AIFS; associated with this, there is also a shorter contention window. The transmitter then gains access to the channel in the normal way, but in view of the shorter AIFS and shorter contention window, this means a higher chance of it gaining access to the channel.

The HCCA adopts a different technique; it can offer guarantees about the level of service it can provide, and thereby providing a true QoS service. The control station, which is normally the AP, is known as the Hybrid Coordinator (HC). The HC manages the wireless medium access to provide parameterized QoS. HCCA uses a polled-based mechanism to access the medium, thereby reducing contention on the wireless medium.

There are still a number of problems to overcome before QoS is fully implemented on Wi-Fi. Nevertheless, IEEE 802.11e is a major step in the right direction, and vendors of Wi-Fi products are already adopting the standard. As such this makes it an important step forward in ensuring that Wi-Fi meets the growing demands being placed upon it.

The IEEE 802.11 handover process refers to the mechanism on which APs and MNs exchange messages that in the end result in a transfer of physical layer connectivity. Inter Access Point Protocol (IAPP) is one protocol that enables MN to jump from one AP (prior-AP) to other AP (posterior-AP). The state information that is transferred typically consists of client credentials.

The complete handover process is composed by two processes: discovery and re-authentication. The discovery process is the phase where the MN, normally due to mobility, after losing connectivity with the prior-AP, starts to initiate a handover. Thus, the client needs to find the potential ranged APs to associate to. This step is referred to as scan in MAC nomenclature. There are two methods of scanning, passive an active. In active scanning, apart from listening to beacon messages, the MN sends additional probe broadcast packets on each channel. The beacon includes information such as Service Set Identifier (SSID), supported rates and security parameters. The selection of which AP to use depends on several parameters, e.g. signal quality, AN capabilities and user preferences.

After locating and deciding about the next AP, in the re-authentication logical step, the MN attempts to re-authenticate to the posterior-AP. This process involves an authentication and a re-association to the new AP, involving a negotiation regarding the communication data rate. The new authentication phase involves the transfer of credential and their state information from the prior-AP.

2.2. IEEE 802.21

The IEEE 802.21 (or Media Independent Handover – MIH) [39] technology is an enabler for the optimization of handovers between heterogeneous IEEE 802 systems, as well as between 802 and cellular systems. The goal is to provide the means to facilitate and improve the intelligence behind handover procedures, allowing vendors and operators to develop their own strategy and handover policies. For this purpose, the IEEE 802.21 aims at optimizing the handover procedure between heterogeneous and homogeneous networks by adding a technology independent function (Media Independent Handover Function – MIHF), which improves the communication between different entities, either locally (mobile node) or remotely (network functions). Sharing information allows handover algorithms to guarantee seamlessness while moving across different points of attachment in the network, and the use of common commands greatly simplifies the design of the algorithms.

The IEEE 802.21 standard provides link layer intelligence and other related network information to upper layers to optimize handovers procedures. The standard can support handovers for both mobile and stationary users. For mobile users, handovers may occur due to a change in wireless link conditions or a gap in radio coverage resulting from movement of the client. For stationary users handovers may occur when the environment around the user changes to make one network more attractive than another.

The IEEE 802.21 standard supports cooperative use of mobile clients in addition to the network infrastructure. The mobile client is capable of detecting available networks, and the infrastructure can store required network information, such as neighborhood cell lists and the location of mobile devices. In general, both the client device and the network's Points of Attachment (PoA) can support multiple radio standards (multimode) and in some cases use more than one interface simultaneously.

The standard provides an architecture to support transparent service continuity while a MN switches between heterogeneous link layer technologies. This architecture relies on the identification of a mobility-management protocol stack within the network elements. As shown in Figure 2-8, handover-enabling functions within the mobility-management protocol stack include the new entity, the MIHF. The standard also defines various Service Access Points (SAPs) and associated primitives that provide access to the MIH function services.

Figure 2-8 depicts the IEEE 802.21 reference model with functional entities and associated interfaces, where the MIH technology is implemented in the mobile nodes and network side components, both being MIH-enabled.

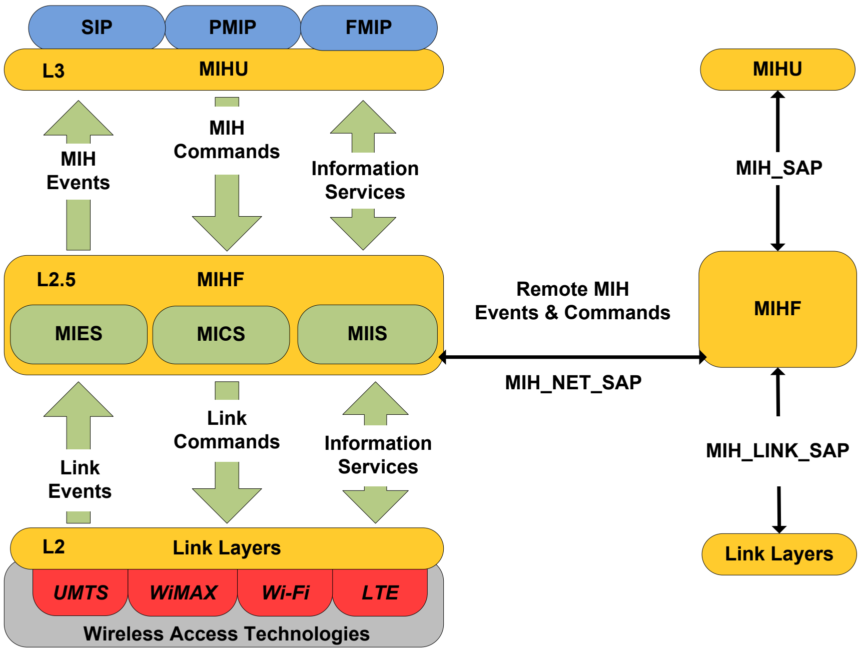

Figure 2-8: IEEE 802.21 framework

The information exchange occurs between lower layers and higher layers, taking always the MIHF as reference. Furthermore, information can be shared locally, within the same protocol stack, or remotely, between different network entities.

The IEEE 802.21 architecture is defined considering the MN as the central point. Two definitions that are being used commonly through this document are the concepts of PoA and Point of Service (PoS). In the following, the definition of these two concepts is introduced:

- *PoA*: network side endpoint of a layer 2 link that includes a MN as the other endpoint;
- *PoS*: network-side MIHF instance that exchanges MIH messages with an MN-based MIHF.

Figure 2-8 also presents the three more important SAP specified in IEEE 802.21:

- *MIH_SAP*: media independent interface of MIHF with the higher layers or MIH users;
- *MIH_LINK_SAP*: abstract media dependent interface of MIHF with the lower layers (the different technologies);
- *MIH_NET_SAP*: abstract media dependent interface of MIHF providing transport services over L2 and L3 over the data plane. This SAP supports the exchange of MIH information and messages with a remote MIHF or a media independent Information Server (IS).

2.2.1. Media Independent Handover Services

The IEEE 802.21 framework provides three primary services: (i) Media Independent Event Service (MIES), (ii) Media Independent Command Service (MICS) and (iii) Media Independent Information Service (MIIS). The aforementioned services will be described in the following sections.

2.2.1.1. Media Independent Event Service

Handovers may be initiated by the MN or the network. The associated events may originate from the MAC, PHY or the MIHF at the MN, at the network PoA, or at the PoS. Thus, the source of these events may be either local or remote. Local events take place within a client whereas remote events take place in the network elements. The event model works according to a subscription/notification procedure. A MIH user (typically upper layer protocols) registers to the lower layers for a certain set of events and gets notified as those events take place. In the case of local events, information propagates upward from the MAC layer to the MIH layer and then to the upper layers; this also divides the events into two broad categories – Link events and MIH events. Link events are events that originate from event source entities below the MIHF and may terminate at the MIHF. Entities generating Link events include, but are not limited to, various IEEE 802-defined, 3GPP-defined, and 3GPP2-defined interfaces. Within the MIHF, Link events may be further propagated, with or without additional processing, to MIH users that have subscribed for the specific events. MIH events are defined as events created within the MIHF, or Link events that are propagated by the MIHF to the MIH users. Above the MIHF, multiple higher layer entities may be interested in these events at the same time. Hence the events can have multiple destinations, and the MIHF may help in dispatching these events to multiple destinations. In the case of remote events, information may propagate from the MIH or layer 3 mobility protocols in one stack to the MIH or layer 3 mobility protocols in a remote stack.

Some of the common events defined include *Link_Up*, *Link_Down*, *Link_Parameters_Report*, *Link_Going_Down*, etc. Basically MIES provides triggered events corresponding to dynamic changes in the link characteristics and link status. As the upper layer gets notified about certain events it makes use of the command service, discussed in section 2.2.1.2, to control the links to switch over to a new PoA. Figure 2-9 illustrates the Media Independent Event Service (MIES).

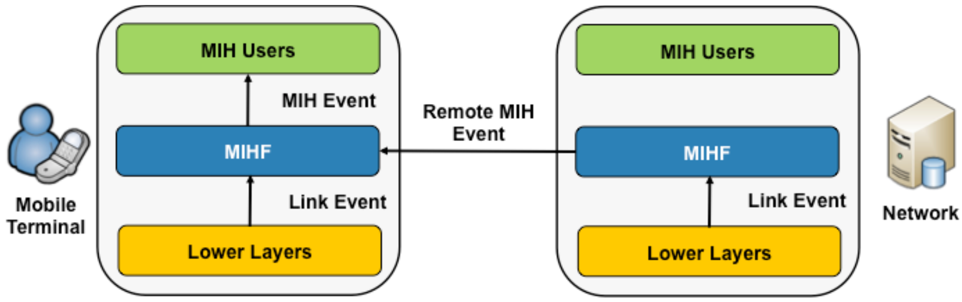

Figure 2-9: MIES operation

2.2.1.2. Media Independent Command Service

Media Independent Command Service (MICS) basically helps the MIH user to manage and control the link behavior of the multi-mode devices and optimize performance with regard to handovers and mobility.

Contrary to what was discussed in MIES, the commands are sent from MIH users to lower layers in the reference model. MICS may also enable MIH users to facilitate optimal handover policies. For example, the network may initiate and control handovers to balance the load of two different access networks.

A number of commands are defined in this standard to allow the MIH users to configure, control, and retrieve information from the lower layers including MAC and PHY. The commands are classified into two categories: MIH commands and Link commands.

The receipt of certain MIH command requests may cause event indications to be generated. The receipt of MIH command requests may indicate a future state change in one of the link layers in the local node. These indications notify subscribed MIH users of impending link state changes. This allows MIH users to be better prepared to take appropriate action. Also MIH commands may be locally or remotely generated.

Link Commands originate from the MIHF and are directed to lower layers. These commands mainly control the behavior of the lower layer entities, and they are local only. Examples of Link commands are *Link_Capability_Discover*, *Link_Event_Subscribe*, *Link_Get_Parameters*, *Link_Configure_Thresholds* and *Link_Action*. Examples of MIH commands are *MIH_Link_Get_Parameters*, *MIH_Link_Configure_Thresholds* and *MIH_Link_Actions*. The commands instruct an MIH device to poll connected links to learn their most recent status, to scan for newly discovered links, to configure new links and to switch between available links. Figure 2-10 illustrates the MICS.

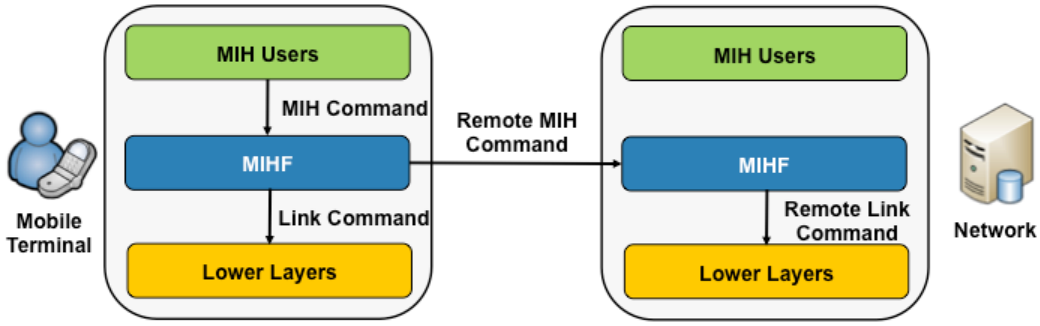

Figure 2-10: MICS operation

2.2.1.3. Media Independent Information Service

As a MN is about to move out of the current network, it needs to discover the available neighboring networks and communicate with the elements within these networks so as to optimize the handover. The Media Independent Information Service (MIIS) provides a framework and corresponding mechanisms by which an MIHF entity residing within the MN or the network can discover and obtain network information within a geographic area. MIIS primarily provides a set of Information Elements (IEs), the information structure and its representation, and a query/response type mechanism. IEs provide information that is essential for a network selector to make intelligent handover decisions. MIIS provides static information about different ANs, such as current available resource levels, state parameters, while dynamic statistics should be obtained directly from the respective ANs.

Some of the key motivations behind the MIIS are:

- Provision of information about the availability of ANs in a geographical area. Further, this information could be retrieved using any wireless network, for example information about a nearby Wi-Fi hotspot could be obtained using a GSM, CDMA or any other cellular network;
- Provision of static link layer information parameters that could help the MNs in selecting the appropriate AN. For example, knowledge of whether security and QoS are supported on a particular AN may influence the decision to select that particular network during handover;
- Provision of information about capabilities of different PoAs in neighbor reports to aid in configuring the radios optimally for connecting to available/selected ANs. In the case of static information, for example, knowledge of the supported channels by different PoAs may help in configuring the channels optimally as opposed to scanning or beaconing and then finding out this information. However, for the most part, dynamic link layer parameters have to be obtained or selected based on direct interaction with the ANs as MIIS may not be much help in this regard;

- Provision of an indication of higher layer services supported by different ANs and CNs that may aid in making handover decisions. Such information may not be available directly from the MAC sublayer or PHY of specific ANs, but could be provided as part of the MIIS.

Table 2-4 exemplifies the usage of the MIIS.

Table 2-4: IS containers example

Network Type	SSID / Cell ID	Operator	Security	EAP Type	Channel	QoS	Physical Layer	Data Rate
GSM	13989	Oper-1	N/A	N/A	1900	N/A	N/A	9.6 Kbps
802.11n	Enterprise	Oper-2	802.11i	EAP-PEAP	6	802.11e	OFDM	100 Mbps
WiMAX	N/A	Oper-3	PKM	EAP-PEAP	11	Yes	OFDM	40 Mbps

2.3. Related Work

Herein the related work for each one of the research topics addressed in this Thesis is depicted.

2.3.1. QoS Control for an All-IP WiMAX Network Architecture

Supporting multimedia applications with different QoS requirements in the presence of diversified wireless access technologies is one of the most challenging issues for 4G wireless networks [48]. The Internet was originally developed to offer “best effort” communication services, wherein all data was to be treated equally without any QoS bounds or guarantees regarding delivery. However, with the emergence of real-time communication such as VoIP and video streaming, e.g. Video on Demand (VoD), strict QoS requirements were put on the Internet in terms of delay, jitter and throughput. This led to the development of the present day QoS models that can support required communication QoS on the Internet [49].

According to the ITU, QoS is the “collective effect of service performance which determines the degree of satisfaction of a user of the service” [50]. Likewise, it must be considered QoS from the network point of view, which is the capability that a network component (e.g. application, host or router) must have in order to contain some level of assurance so that its traffic and service requirements can be satisfied [51] [52].

QoS is defined as a set of bounds such as latency, jitter, throughput and packet loss to be maintained by the network for a particular data flow. There are two main QoS provisioning models in the Internet that have been developed by IETF: (i) Integrated services (IntServ) and (ii) Differentiated services (DiffServ) [31]. The stateful IntServ [30], which maintains per-flow reservation state at QoS network entities, has a greater level of accuracy and a finer level of granularity. The stateless DiffServ does not maintain per-flow reservation state at QoS network entities and only relies on coarse classification and differential treatment of traffic.

EuQoS (End-to-end Quality of Service support over heterogeneous networks) was a research project sponsored by the EU with a three years duration (2004 – 2007) [53]. The main aim of EuQoS was to build an entire QoS framework, addressing all the relevant network layers, protocols, and technologies. The EuQoS project proposed and developed new QoS mechanisms that incorporate the following components: monitoring and measurement, admission control, failure management, signaling and service negotiation, security, charging, traffic engineering and resource optimization. The design, implementation and test of a complete system to solve the problem of finding and providing end-to-end QoS paths between users connected through heterogeneous access networks was the main target of the EuQoS research project. This framework, which includes the most common ANs (xDSL, UMTS, Wi-Fi, and LAN), was prototyped and tested in a multidomain scenario throughout Europe, composing the so-called EuQoS system. Under the EuQoS scope, a set of relevant scientific research papers for this Thesis was published [54] [55] [56] [57]. The next paragraphs analyze the major outcomes of these scientific works.

In [54] the authors presented an approach for QoS provisioning for Ethernet-oriented network access environments, based on the emerging Next Steps In Signaling (NSIS) framework. In order to evaluate and validate the use of NSIS and its ability to support traffic differentiation in Ethernet, a preliminary simulation study was performed. To study the advantages of using priorities in Ethernet networks, the authors evaluated the transmission of different types of traffic in different topologies. The results showed that without QoS prioritization made through NSIS, all the traffic presents similar behavior, experiencing high delay in the face of network congestion. On the other hand, when using the NSIS-based resource allocation for VoIP traffic, the VoIP delay remains low during all the simulation. Therefore, the authors showed that NSIS-based signaling enables traffic differentiation.

In [55] the authors put the focus on the Common Open Policy Service (COPS) and NSIS signaling frameworks. The analysis of the use of COPS and NSIS to support the signaling and service negotiation functions revealed that these protocols can be used to provide a basis to support the desired functionality and a framework for further enhancements. Simulation results using Ethernet ANs showed that the signaling framework composed by NSIS and COPS has potential to control underlying network devices and improve the QoS provided to applications.

In [56] the authors described all the developed and tested mechanisms which were used for interdomain QoS routing and signaling. From a signaling and service negotiation perspective, the presented architecture encompasses support for application signaling, horizontal signaling between the resource managers from each domain and vertical signaling between the resources managers and the resource technology allocators. The horizontal signaling is made through an extension of the NSIS protocol and allows the signaling and QoS requirements exchange between the different network domains. The vertical signaling is achieved with an extended version of the COPS protocol. From a QoS routing point of view, an extended version of the BGP protocol was used for interdomain routing. The QoS routing performance was evaluated and validated through simulations. They pointed out that the preliminary results in terms of performance validated all the design issues for system.

In [57] is given a detailed description of the EuQoS architecture, focusing on its QoS model, architectural components and resource provisioning styles, including the NSIS protocol for horizontal QoS signaling in heterogeneous network environments. The effectiveness of the proposed architecture is testified by the results obtained in a prototype implementation installed on the EuQoS pan-European testbed, consisting of twelve local testbeds connected to the respective National Research and Education Networks (NRENs) and interconnected through the GEANT European backbone networks. Each local testbed implemented different access technologies (UMTS, Wi-Fi, xDSL and Ethernet). The prototype tests confirmed the expectations related to the actual QoS perceived by the users, even in the presence of heavy cross-traffic. On the other hand, they show that, although within the computational limitations of a prototype, the EuQoS signaling architecture is able to support a suitable load for a real large-scale network environment.

The results presented in articles [54], [55], [56] and [57] predict the use of the NSIS signaling protocol to establish QoS signaling in next generation QoS frameworks. To evaluate and validate the proposed QoS architecture, performance measurements were made in a simulator and in a pan-European prototype connected through the GEANT European backbone network. However, the authors did not study the NSIS protocol for signaling end-to-end QoS requirements. In fact the NSIS protocol was used only on the core side of the network, requiring another protocol to establish the signaling between the end user device and the NSIS network node. Beyond this limitation related with NSIS, the range of access technologies used was vast, including both wired (e.g. Ethernet, xDSL) and wireless (e.g. Wi-Fi, UMTS) technologies. On the one hand, this represents a great heterogeneity regarding the different types of access technologies involved, but on the other hand, it is not thoroughly studied the impact of the proposed QoS framework in each one of the access technologies. Furthermore, 4G wireless access technologies, such as WiMAX and LTE, are not part of the study.

DAIDALOS (Designing Advanced network Interfaces for the Delivery and Administration of Location independent, Optimized personal Services) was a significantly large European research project split in two phases, the first one between 2003 and 2006 and the second phase from 2006 to 2009, also known as DAIDALOS I and DAIDALOS II, respectively [25] [26]. DAIDALOS goal was to define a network architecture to provide ubiquitous access integrating heterogeneous ANs (Wi-Fi, UMTS, WiMAX, MBMS – Multimedia Broadcast and Multicast Services, and DVB) and providing seamless movement among them. The architecture supported also the following features: (1) mobility management is split between local and global domains; (2) handovers with QoS through a common framework for mobility and QoS signaling in heterogeneous technology networks, (3) host multihoming – the host owns multiple physical network interfaces and concurrently gets access through them; (4) integrates broadcast networks, also considering unidirectional networks without return channel and (5) integrates ubiquitous and pervasiveness concepts for customized services to the users.

During the first phase of DAIDALOS (2003 – 2006), several research papers related with end-to-end QoS and WiMAX access networks integration were published [58] – [66]. DAIDALOS I was the basis of the research work developed in the scope of this Thesis.

In [58] and [59] it is presented a next-generation 4G architecture focused on the different QoS signaling strategies that can be used. The papers depicted the pros and cons with regard to session setup and negotiation for each QoS signaling solution. The signaling strategies analysis is made according to three major scenarios: (1) terminal initiated (explicit) signaling – the MN itself (e.g. QoS client) performs the QoS requests to a QoS broker in charge of resource management at the AN); (2) application-provider controlled signaling – a service proxy (e.g. SIP proxy) is responsible for requesting network resources to the QoS broker; (3) network controlled (implicit) signaling – a novel network entity collocated at the access router, capable of QoS and application signaling, intercepts the data packets and issues the QoS requests. The authors concluded that each QoS scenario should be associated to a QoS model (MN, network service or application service oriented), being directly related to the business model chosen by the network operator.

As a follow-up of the work presented in [58] and [59], the authors presented in [60] the results of the experimental evaluation for the different QoS signaling strategies: implicit, explicit and proxy-based signaling. The evaluation is based on evaluating the session setup and negotiation provided by each signaling solution on an experimental testbed. The results indicated that the implicit and explicit QoS signaling were fast, approximately 25 ms and 35 ms, respectively. Regarding the multimedia-based proxy signaling, more interesting for 3GPP-based systems, showed reasonably performance, 150 ms.

The aforementioned papers ([58], [59] and [60]) discussed very interesting and detailed end-to-end QoS signaling strategies for different scenarios and purposes. Nevertheless, although the authors argue that the described QoS signaling strategies are generic, the NSIS protocol is not analyzed and the impact of its integration is not evaluated. Moreover, the integration with wireless access technologies is also not addressed.

In [61], [62] and [63] the authors described a modular architecture which provides seamless QoS support over different wireless technologies for the AN, and describes the appropriate interface with CN to perform end-to-end QoS. The architecture is composed by two main modules: Abstraction Layer (AL), which provides communication with the CN to perform management, and Abstraction Layer Driver (ALD), which is technological dependent and performs QoS operations regarding each technology. The proposed architecture provides the following features: scalability – any new coming access technology can be merged in the architecture just adding the correspondent AL-driver module; support for complex scenarios – the two-hop capability allows concatenation of two different technologies to extend the access network; and integration with other functionalities: appropriate interfaces were defined in order to provide compatibility with mobility, security and multicast.

The work presented in [61], [62] and [63] provide an end-to-end QoS-enabled architecture for different wireless technologies, including cross-layer interactions between the layer 3 network entities and pre-WiMAX compliant equipments. However, the end-to-end NSIS QoS signaling protocol is not addressed, and the pre-WiMAX technology is deprecated. Furthermore, the studied scenario was limited to fixed pre-WiMAX applied to concatenated pre-WiMAX and Wi-Fi scenarios. Performance results are not presented as well.

In [64], [65] and [66] the authors presented key aspects of an architecture which is able to bring fixed pre-WiMAX technologies into play for the future 4G networks in compounded wireless environments. The architecture overcomes the shortcomings of the pre-WiMAX technology, allowing real-time services to be used in a dynamic environment, where users roam across Wi-Fi access points. For reaching this objective, both virtual MAC addresses and auxiliary channels were used. The proposed methodology addresses the dynamic problems by temporary allowing traffic to flow in a reserved channel, thus providing temporary better QoS assurances to traffic flows. Furthermore, a global QoS abstraction layer had to be developed to support end-to-end QoS in the wireless link. A field demonstrator was developed with pre-WiMAX equipment, as part of a larger demonstrator. Experimental results for the wireless access were obtained showing that reservation times are very small and perfectly capable to be integrated in 4G environments, providing QoS differentiation in such an heterogeneous environment.

As mentioned before, the work reported in [64], [65] and [66] was the ground basis for the research work made in this Thesis. However there are some limitations associated with this proposal: (1) for each application service, it was mandatory to create a group of background SFs to transport the data packets while the dedicated SFs were being created in the WiMAX technology (QoS reservations were very time-consuming – approximately 20 seconds); (2) only 802.3 Ethernet classifiers were defined which implied the definition of virtual MAC addresses and complex translation mechanisms in both the BS and the SS to enable services differentiation for the same user; (3) no support for QoS flows modification; (4) the interface with the pre-WiMAX system was very limited (HTTP) for an environment with real-time services; and (5) the architecture was designed for fixed pre-WiMAX networks backhauling Wi-Fi access links.

During the second phase of DAIDALOS (2006 – 2009), the work developed during the first phase was enhanced, as reported in the following scientific publications [67] [68] [69]. Please notice that DAIDALOS II ran in parallel with the elaboration of this Thesis.

In [67] the authors presented a QoS architecture to seamless integrate heterogeneous networks with different technologies, including broadcast ones, taking into account context information to enhance the user expectation. The presented architecture is able to seamless support multihomed users connected to different available networks, where mobility is inherently integrated in the QoS approach. The authors consider the NSIS protocol for the end-to-end QoS signaling procedures. Inter-domain QoS is also supported through federation concepts and dynamic negotiation of needed services and amount of resources. A monitoring system to aid in admission control decision process and to increase the resource network utilization is integrated in this architecture. In [68] and [69] it was addressed a next generation end-to-end QoS architecture, based on existing standards, adequately extended, and with support for QoS at layer two and three. A Radio Access Layer (RAL) is proposed to deal with the specific QoS characteristics of each access technology. In this case, the NSIS signaling protocol is used for explicit signaling procedures and the architecture is able to support mobile access technologies. Nevertheless, performance measurements for the NSIS signaling strategy are not presented and details for the integration of the wireless access technologies, and specifically for the WiMAX case, are not given.

2.3.2. Seamless Mobility Support in WiMAX Access Networks

The work in [70] presented two handover protocols for the IP layer and the MAC layer used in future mobile networks: FMIPv6 and IEEE 802.16e. FMIPv6 was developed to overcome the inadequacy of MIPv6 in achieving seamless handover, but the proper behavior of FMIPv6 is strongly dependent on indications from the link layer and physical layer. It is created a cross-layer design to enable proper FMIPv6 operation with the IEEE 802.16e handover procedure and it is provided three events and one command for supporting the interaction between the IP layer and the MAC layer handover procedures.

In the research elaborated in [71] it is proposed a handover procedure combining IEEE 802.16e, FMIPv6, SIP, and IEEE 802.21, which ensures explicit handover between IEEE 802.16e wireless network and upper layers to provide seamless handover without packet loss. It is presented a multi cross-layers design, which employs MIH framework to combine the IEEE 802.16e wireless network with the upper layers to achieve seamless handover. With four triggers, an integration of fast handover and SIP mobility control mechanism can be used to prevent packet loss and support fast moving objects.

The research work presented in [72] described a solution for macro mobility in an all-IP network with WiMAX as the access technology. The proposed approach has been implemented on a testbed and evaluated in order to address the impact of the developed mechanisms upon the overall system performance. The results have shown that the mobility mechanisms introduce a rather small overhead, while having the capability to support a *make-before-break* handover process.

In [73] the authors proposed a fast PMIPv6 scheme over IEEE 802.16e access networks and defined two link-layer and two network-messages to reduce the handover latency and packet loss. It is also evaluated the performance of the proposed scheme compared with the standardized PMIPv6 and the FMIPv6. As a result, the authors argue that the performance of the proposed scheme is better than others, since fast binding-update enables the packets from the Local Mobility Anchor (LMA) to be efficiently forwarded directly to the new Mobile Access Gateway (nMAG). In the proposed scheme, handover latency is less than the PMIPv6 and packet loss does not occur. It is able to efficiently forward packets from the LMA by using fast binding-update.

In [74] the authors presented a cross-layer design, which employed MIH to combine IEEE 802.16e with IP layer, to achieve seamless handover. With pre-binding update and IEEE 802.16e handover indication, an integration of fast handover control mechanism can be used to prevent packet loss and support fast moving devices. Performance analysis showed that the proposed method can achieve lowest handover delay with lower signaling cost.

In [75] it is proposed to use MIP in mobile WiMAX for interdomain (inter-CSN) mobility management and a fast handover protocol, named Fast Intra-Network and Cross-Layer Handover (FINCH), for intradomain (intra-CSN) mobility management. The protocol is discussed with some examples. The analytical models and extensive simulations showed that the proposed FINCH can support fast and efficient link layer and intradomain handovers. Because of the cross-layered design, comparing with other intradomain mobility management protocols, the proposed FINCH reduces location update cost and overall cost. Comparing with MIP, the proposed FINCH does not need IP encapsulation and does not have triangular routing problem. It also reduces the overhead caused by registering CoA with the HA. By unifying the mobility management in layer 2 and layer 3, the overhead and latency in interfacing conventional mobility management protocols in the two layers are eliminated as well.

The work published in [76] described a cross-layer IPv6 fast handover network architecture for IEEE 802.16e to accommodate the delay sensitive real-time applications. The total handover delay and the service disruption times are reduced by integrating the link layer and IP layer messages and by using a fast network re-entry mechanism in IEEE 802.16e. The performance analysis results showed that the proposed cross-layer framework features have a much smaller service disruption time than the FMIPv6 over IEEE 802.16e scheme.

By considering the correlation between layer 2 and 3, in [77] it was proposed a cross layer scheme to reduce the overhead of the handoff procedure. The L2 and L3 handoff messages were smoothly combined so that the total number of handoff messages can be reduced. The obtained results showed that the handoff delay of the proposed scheme was lower to that of the other scheme because the number of control message was reduced.

In [78] the authors proposed a mechanism which incorporates information from several layers to speed up the layer 2 handover. It was shown through simulations that the new mechanism decreases the handover latency significantly. [79] emphasized the benefits of using a flat architecture for mobile WiMAX networks for data-centric wireless services. A cross-layer solution for efficient handover in the flat architecture mobile WiMAX networks was described. Simulations indicated that a satisfactory handover performance could be achieved.

In [80] the authors described a fast handover scheme along with a new transport CID mapping strategy for real-time applications. Simulations showed that through the proposed schemes, the handover latency for both downlink and uplink services is reduced.

2.3.3. Optimized Fusion of Heterogeneous Access Network based on Media Independent Handover Framework

In the near future wireless networks will be spread and available for the end-users. In such heterogeneous wireless networks, the vertical handover procedures and the optimized fusion of wireless access technologies is critical [81], as indicated in the research works published in [82] and [83].

In [82] it is addressed the integration of mobile WiMAX with evolved 3GPP networks as a typical and commercially compelling example of deploying heterogeneous next-generation mobile networks. The architecture and key procedures that enable WiMAX and 3GPP integration are investigated, and a novel handover mechanism that enables seamless mobility between mobile access technologies with single radio mobile terminals is introduced.

[83] proposed a fully terminal-controlled mobility solution across heterogeneous networks without any architectural change in network operators' infrastructure. A user-centric network selection policy that gives users the freedom to select the best access network to maximize their satisfaction is described. The authors argue that the proposed solution is realistic and not very complex to implement in current mobile devices and networks.

For vertical handover signaling, IEEE introduced the 802.21 Media Independent Handover (MIH) framework [84] [85] to optimize the discovery, decision, execution and completion procedures of the handover process. Several research papers have already been published with the optimization details provided by the IEEE 802.21 framework in vertical handover procedures [84] – [88]. Moreover, several proposals to further optimize the MIH platform have also been published [89] - [94].

In [89] it is investigated and analyzed how to extend the current SIP based Network Mobility (SIP-NEMO) to support multihoming further. The proposed multihomed SIP-NEMO is simulated in different cases and integrated with the IEEE 802.21 standard. According to the simulation results, the SIP-NEMO can keep route optimization no matter which multihomed case is configured.

A network-initiated handover scheme based on the IEEE 802.21 framework, which guarantees the QoS service continuity in UMTS/802.16e networks, is proposed in [90]. New QoS-related MIH primitives are specified and a network-initiated handover procedure considering QoS service continuity is designed. As a result, the performance of the proposed handover procedure outperforms the existing handover procedure based on the IEEE 802.21 framework.

[91] proposed a load balancing mechanism for reducing the queuing delay in MIH based PMIPv6 networks. Simulation and analytical results demonstrate that the proposed load balancing mechanism reduces the average queuing delay and increases the data transmission rate from each PoA.

[92] described a user-adaptive vertical handover scheme based on MIH function in the integration of Wi-Fi, WiMAX and UMTS networks environment. Users' QoS demands are given full consideration throughout the whole handover procedure. From the user's point of view, the proposed scheme adopts two kinds of handover triggers considering the user's QoS demands as well as the link layer conditions, which can improve the provided service quality. A Multiple Attribute Decision Making (MADM) method, which utilizes IS information, is described. Simulation results show that the proposed scheme provides less handover times and better QoS than basic handover scheme.

In [93] it is proposed a mechanism that optimizes the FMIPv6 handover procedure with the assistance of IEEE 802.21 MIH services for vehicular networking. New functionalities are defined for the 802.21 MIIS to contain the L2 and L3 information of neighboring access networks, which can help the FMIPv6 protocol to tackle issues such as radio access discovery and candidate AR discovery. The authors show, through analytical and simulation results, that the proposed mechanism applied to FMIPv6 increases the probability of the predictive mode of operation and reduces the overall (both layer 2 and layer 3) handover latency, outperforming the original FMIPv6 protocol.

A mechanism to optimize the PMIPv6 handover process with the assistance of IEEE 802.21 MIH services is described in [94] [95]. The mechanism performs proactive signaling among the PMIPv6 domain elements hence eliminating the authentication delay from the actual handover process. Therefore, neighboring MAGs have information about each other as well as attached MNs hence helping PMIPv6 to tackle the issue of access authentication in advance. The mechanism, therefore, reduces handover delay significantly by eliminating the authentication as well as the attachment notification phases from the actual handover process. Through analysis of the signaling procedures, it is shown that the mechanism performs better than basic PMIPv6 and the host-based HMIPv6 in terms of reducing handover delay.

Other research efforts have examined critical aspects of the handover procedure. When, for example, security is considered, then the handover procedure is shorten in time and service disruption could become unnoticeable if security associations and configurations are performed at higher layers before the MN moves to the new network [96]. Another significant aspect is the handover decision and the sophisticated management of the underlying link-layer interfaces. Similarly with the previous case, the standard MIH functionality does not support these operations, but they can be added using an extra module embedded in the MN for efficiency and flexibility [97].

From an architectural point-of-view, the location of MIH functionality has been also examined for an integrated WiMAX/3GPP network case [86] [98]. Security and scalability is improved when MIH-enabled nodes are chosen carefully whilst nodes that execute critical operations (such as the handover decision mentioned earlier) are placed deeper in the core network, minimizing, that way, any MIH signaling between network entities. Finally, the accurate mapping of MIH messages to link layer primitives was identified as a key factor towards efficient use of network interfaces [98].

Regarding the use of SIP for mobility management, in [99] it is presented the benefit of adopting MIH to optimize SIP-based vertical handover procedures. The concept of SIP intelligent handover for intra domain mobility using a network-assisted, MN-controlled approach is described.

The interest on the fusion of different access technologies using the IEEE 802.21 protocol has triggered much research effort from both the industry and the academia. Related efforts by major telecommunications vendors mainly focus on basic MIH functionality for specific handover scenarios, such as the Wi-Fi to WiMAX handover as demonstrated by Intel [101] or the joint test-bed used by InterDigital and British Telecom [102] to demonstrate both the viability and the performance of IEEE 802.21 MIH protocol in an emulated IMS framework. The aim of such efforts is to provide a proof-of-concept for the IEEE 802.21 functionality and highlight its benefits for the end user in terms of service provision.

With respect to standardization bodies, 3GPP and WiMAX Forum are also addressing interoperability issues, another indication of the high level of interest in this topic. Until this moment, both groups focus and promote their own solutions in order to address inter-technology mobility issues and hence compromise on any possibility for seamless interaction with forthcoming access technologies. Recently, though, these standardization bodies have taken notice of the potential of the IEEE 802.21 standard and started evaluating its impact within their respective architectures.

2.3.4. Context-aware Mobility Management

Context information relevant for vertical handover procedures is distributed on several nodes of the network (e.g. location server, user profile database, access points) and the mobile node, including the user's applications. However, the context information must be collected and provided to the right nodes for handover decision at the right time. For this, the context information should be provided proactively to the mobile node, i.e., before the handover takes place and when the mobile node has good radio connectivity. In [103] the authors provide a general framework for handover decisions which take into account the context of both the mobile network and the user. The presented solution shows how to collect the context, to compile information, and to propagate it proactively. Due to the fast evolving nature of context information, the described flexible framework allows one to update the decision algorithm and the context data.

In [104] the authors describe an architecture that aims at optimizing mobile network services based on context information. It is shown that intelligent handover decisions are important in future, heterogeneous mobile networks with different capabilities. The proposed architecture is able to gather information from different network elements and to use this information on mobile nodes for local context-awareness and better handover decisions. This architecture allows for a flexible use of different protocols to exchange different types of context information, as well as a flexible use of different context-aware decision algorithms on mobile nodes. The evaluation of the proposed architecture, based on a prototype, showed that context-awareness increased the efficiency of handovers.

With regard to novel middleware solutions, [105] proposes the Mobile agent-based Ubiquitous multimedia Middleware (MUM), that performs effective and context-aware handoff management to transparently avoid service interruptions during both horizontal and vertical handoffs. MUM exploits the full visibility of (i) wireless connections available and their handoff implementations (handoff awareness), of (ii) service quality requirements and handoff-related quality degradations (QoS awareness), and of (iii) network topology and local resource availability (location awareness); that visibility enables MUM to provide original solutions for handoff prediction, multimedia continuity via adaptive data buffering/pre-fetching, and proactive re-addressing/rebinding. The reported experimental results demonstrate that the middleware, notwithstanding the flexible application-level approach, can effectively maintain service continuity in application deployment environments with the typical QoS requirements of current Internet streaming, even in the case of vertical handoff between different connectivity technologies such as from Wi-Fi to Bluetooth.

An overview of the vertical handover decision process with a classification of the different existing vertical handover decision strategies is described in [106]. It was showed that advanced evaluation functions and optimized architectures are needed to perform better handover decision making for user satisfaction as well as for the efficient use of network resources. So, to build a handover management solution, some issues have to be considered in the choice of a vertical handover decision strategy: handover control (at the mobile terminal or network), information gathering, handover execution procedure, more available access networks and handover performance evaluation.

In [107], the authors investigate the use of the Service-Oriented Architecture (SOA) features in wireless networking environments and propose a SOA for network discovery and selection. Moreover, the authors discuss the technologies that can be used in this architecture for dynamically updating real-time network state information without causing heavy overhead load. The developed architecture is network-independent, thus applicable in the envisioned future networks.

As mentioned in [108], the discovery of currently available Radio Access Networks (RANs) is really challenging, especially in terminals with Wi-Fi support. Their work uses the IEEE 802.21 framework to exploit neighboring Wi-Fi information as fast as possible, avoiding battery energy waste. Their simulation results show that the proposed scheme can improve MN´s battery time and Wi-Fi detection time compared to conventional full scanning Wi-Fi procedures. They also show that selective scanning procedures are much better than those of full scanning.

A recent work [109] sustains that a seamless handover procedure requires that the MN discovers the parameters of the networks in its surrounding area prior to establish an association with the candidate network. Thus, it proposes an architecture using the IEEE 802.21 MIIS, where several network elements contribute to the network discovery process, in a request-response scheme in two steps. A prototype was implemented with off the shelf hardware and achieved results indicate that the network selection is performed in shorter times when compared to other works.

[110] described a context-aware reconfigurable system, which implements the IEEE 802.21 MIH standard for interoperability between wireless hybrid access networks. The proposed approach uses vertical handover prediction algorithms to improve the resource management decisions, through access to the MIIS, which stores previously acquired information about surrounding hybrid access networks. Various prediction alternatives are discussed, and two proposed algorithms are evaluated on a prototype implementation of the system.

The work presented by [111] extends the MIH framework with a context-awareness module. More specifically, it is presented a context-aware mechanism for generating timely *MIH_Link_Going_Down* (LGD) event that triggers handover preparation before losing the current connection. Experiment results show that the proposed mechanism can generate timely MIH LGD event.

An Enhanced Media Independent Handover Framework (EMIHF) and its mobility management mechanism based on IEEE 802.21 is described in [112]. Comprehensive trigger criteria and handover schemes are provided for seamless mobility management. This mechanism supports adaptive adjustment according to application change, user and network information. Experimental results demonstrate the effectiveness and good potential of proposed approaches.

[113] depicted an Enhanced Information Server (EIS) to accelerate vertical handover procedures in IEEE 802.21 MIH networks. Based on the EIS, the authors propose an improved vertical handover procedure in which wireless channel conditions are estimated by exploiting spatial and temporal locality at the EIS, and therefore time consuming channel scanning procedures can be skipped. Simulation results demonstrate that the proposed scheme can reduce the vertical handover latency under diverse environments.

2.4. Summary

This chapter started by providing the required background information for this Thesis. Specifically, the BWA RATs (Wi-Fi, WiMAX, UMTS/HSPA and LTE) addressed on this Thesis were briefly described from the QoS and mobility procedures perspective, as well as the IEEE 802.21 MIH framework and core functionalities.

Thereafter, the related research work for each one of the core objectives of this Thesis was presented:

- QoS control for an All-IP WiMAX network architecture;
- Seamless mobility support in WiMAX ANs;
- Optimized fusion of heterogeneous wireless ANs based on MIHs;
- Context-aware MIHs.

In what the QoS control for an all-IP WiMAX network architecture is concerned, several research papers and European projects (EuQoS, DAIDALOS I and II) were described [48] – [69]. Part of the presented research publications [54] – [57] provided important enhancements related with the integration of wireless systems with end-to-end QoS protocols and architectures, but details about the integration with the access technologies and specifically with WiMAX are missing. In the remaining presented literature [58] – [69], cross-layer frameworks between the network layer and WiMAX access network are described, however there is lack of details on the WiMAX access technology. Specifically, further studies are required on the WiMAX QoS procedures (e.g. SFs reservation, modification, deletion), as well as on the integration between the link layer QoS primitives and the upper layer end-to-end QoS protocols. Furthermore, the depicted proposals are not aligned with the WiMAX Forum NRM and most of the cases do not provide an evaluation of the designed and implemented approach. To finalize, it is not addressed the challenging issue of supporting several types of WiMAX equipments from different vendors, either fixed or mobile.

With regard to the seamless mobility support in WiMAX access networks, the described research publications [70] – [80] proposed the integration of IEEE 802.16e with upper layer mobility management protocols. Nevertheless, they do not consider the integration with the WiMAX Forum backbone communication protocols, as well as with end-to-end QoS protocols. Additionally, only a few set of IEEE 802.21 events and commands are integrated, without providing further details about the integration with the IEEE 802.16g protocol. Finally, no simulation or experimental-based measurements are given.

On the optimized fusion of heterogeneous wireless access networks research topic, many proposals are available on the literature, as described in [81] – [102]. The proposed mobility architectures for heterogeneous wireless access environments are based on (i) cross-layer mobility optimizations through IEEE 802.21 and (ii) MIP mobility management protocol, or one of its variants (FMIP or PMIP). However, there is still missing detailed integration of the IEEE 802.21 cross-layer framework (events and commands) with each one of the wireless access networks (e.g. Wi-Fi, UMTS/HSPA and LTE), more precisely the translation of the IEEE 802.21 primitives to the primitives and parameters of each specific access technology. Additionally, it is also missing cross-layer QoS reservation procedures interwined with the cross-layer mobility management procedures, as well as a vertical, IEEE 802.21-enabled, mobility manager to control the inter-technology handover procedure. Finally, another important aspect is related with the different architectural choices for implementing the IEEE 802.21 framework, more specifically with the location of the IEEE 802.21 PoS.

Finally, on the context-aware MIHs subject, the depicted research publications [103] – [113] addressed the positive impact that static and dynamic context information has on the vertical handover decision algorithms. Some of these publications [108] – [113] already enhanced the context-aware mobility procedures with the IEEE 802.21 framework. Nevertheless, none of them has integrated dynamic context-aware information with the IEEE 802.21 IS, as well as context-aware information transport in IEEE 802.21-enabled networks. Furthermore, it is also necessary to evaluate the impact that the integration of context information in the IEEE 802.21 IS has on the inter-technology mobility procedures, particularly in each one of the mobility phases (initiation, preparation, execution and termination).

Based on the open issues retrieved from the related work described above, the remaining chapters of this Thesis depict the proposals made for addressing each one of the research topics addressed. Summarizing, chapter 3 provides an overview of the target BWA scenarios that are foreseen on this Thesis, whereas chapter 4 and chapter 5 dives into WiMAX and the required cross-layer mechanisms to integrate this access technology with the upper layer QoS and mobility procedures, respectively. Subsequently, chapter 6 addresses the coexistence of several RATs in heterogeneous wireless access environments from the QoS and mobility perspective and, to finalize, chapter 7 optimizes the vertical handover mobility procedures with context-aware information.

3. Novel Scenarios for Future Broadband Wireless Access Networks

Nowadays, users are becoming accustomed with broadband access both at home and at work, which enables a dramatic increase in multimedia traffic. Multimedia traffic here denotes any type of audio/visual content, irrespective of whether it is distributed in real time or on demand. Early on, ordinary users acted mainly as consumers of digital content and information which was mainly created by major producers. Today, however, advances in hardware and the commodity of digital content creation devices (from mobile phones with integrated high-resolution cameras to high-definition cameras with integrated Wi-Fi) have given rise to unprecedented quantities of digital media becoming available online by the users. In the process, users have become competent digital content producers as well as consumers. As more users connect with broadband speeds and can therefore share their digital content online in an expedient manner, more content becomes available for consumption and more people become interested in joining the “broadband experience”.

In the meantime, the Internet has emerged as a critical support infrastructure. With respect to broadband Internet adoption and bridging the so-called digital divide, governments around the world, not only in the European Union, have come up with a range of initiatives.

Given the prohibitive costs of wired infrastructures and the ease of deploying wireless technologies, it is predictable that BWA technologies will play a key role in delivering Internet access to the users.

Current Internet access technologies cannot provide yet broadband access to all areas in a cost-effective manner: they either require a substantial investment in cabling and other infrastructure, or cannot deliver broadband connections to several users round the clock. To address this issue, several proposals have been put forward that improve the efficiency of specific access technologies. For BWA, two promising solutions are foreseen: IEEE 802.16 [19] [20] [21], also known as WiMAX, and LTE [17] [18].

WiMAX is a Broadband Wireless Access (BWA) technology for Metropolitan Area Networks (MANs), based on IEEE 802.16 family of standards. WiMAX is an attractive broadband wireless alternative that can be used in urban and rural areas as well as in more demanding remote locations. By deploying WiMAX, broadband Internet access can be provided at only a fraction of the cost of wiring undeveloped areas. IEEE 802.16 supports fixed Subscriber Stations (SSs), according to the IEEE 802.16d standard [19], and Mobile Nodes (MNs), based on the IEEE 802.16e standard [20]. The later allows for node mobility in broadband wireless MAN scenarios. WiMAX is capable of supporting high-mobility nodes, with velocities exceeding 60 km/h, while delivering application-layer throughput in excess of 100 Mbps. However, the currently available, commercial off-the-shelf (COTS) equipment delivers significantly less application-layer throughput. Using different profiles, WiMAX can cover wide areas, which may reach 15 km in Non-Line-Of-Sight (NLOS) conditions and up to 50 km in Line-Of-Sight (LOS) environments, which is extremely important for rural areas. Using this access technology, operators can reach users distributed over large areas, with low installation costs when compared to fiber, cable or Digital Subscriber Line (xDSL) deployments. Operational and management costs are also expected to be lower, which is an important factor especially when considering developing countries or rural areas.

LTE is the next step forward in cellular 3G services. LTE [17] and LTE-Advanced [18] are the latest 3GPP standards for mobile technologies that previously realized the GSM, UMTS and HSPA network technologies. LTE provides an uplink speed of up to 50 Mbps and a downlink speed of up to 100 Mbps. LTE bandwidth is scalable from 1.25 MHz to 20 MHz, suiting the needs of different network operators that have different bandwidth allocations, and also allow operators to provide different services based on spectrum. LTE, whose radio access is called Evolved UMTS Terrestrial Radio Access Network (E-UTRAN), is expected to substantially improve end-user throughputs, sector capacity and reduce user plane latency, bringing significantly improved user experience with full mobility. With the emergence of Internet Protocol (IP) as the protocol of choice for carrying all types of traffic, LTE is scheduled to provide support for IP-based traffic with end-to-end Quality of service (QoS). Voice traffic will be supported mainly as Voice over IP (VoIP) enabling better integration with other multimedia services.

Summarizing, this chapter presents several LTE and WiMAX based broadband wireless access scenarios ranging from fixed to mobile solutions; from backhaul for coverage extension to last mile connectivity; from business to residential; and from urban to rural and impervious areas [114] [115]. Note that, this list of scenarios is not exhaustive and it is expected that several more scenarios will also emerge.

This chapter is organized as follows: section 3.1 describes possible scenarios for broadband wireless connectivity in fixed and mobile environments. Section 3.2 discusses telemedicine-related scenarios, both for remote long-term patient monitoring and emergency services support. Section 3.3 presents several environmental monitoring scenarios, including a detailed description about a WiMAX-enabled fire prevention testbed planning, implementation and empirical evaluation. Finally, section 3.4 overviews and concludes this chapter.

3.1. Broadband Wireless Connectivity Scenarios

This section presents a set of application scenarios to provide last mile connectivity to Internet users, based either on fixed or mobile versions of the most promising BWA technologies currently available [116] [117]. Section 3.1.1 details fixed broadband wireless scenarios based on the fixed version of WiMAX – IEEE 802.16d. Furthermore, other developments established by IEEE 802.16 working groups are also discussed, which aim at enhancing WiMAX with relay and mesh networking functionalities [118]. Section 3.1.2 focuses on mobile broadband scenarios based on the mobile version of WiMAX, as well as on the LTE standard. Mobility support provided by LTE and mobile WiMAX opens up a different set of business opportunities for operators, turning these technologies appropriated for the next generation of mobile communications, so-called 4G, as users will be able to access a wide range of services while moving. To finalize, this section also addresses the new methods within the IEEE 802.16 working group to deliver even higher data rates, as required by the IMT-Advanced (International Mobile Telecommunications – Advanced) [13] for 4G compliant radio access technologies.

3.1.1. Fixed Broadband Wireless Access

IEEE 802.16 and WiMAX have evolved considerably over the years. Once considered as solely a fixed wireless local loop technology, for the most part suitable only for residential connectivity, WiMAX has emerged as a perfect candidate for providing BWA in numerous and quite diverse fixed scenarios, as explained in the remaining of this section. WiMAX can backhaul traffic from other technologies, such as Wi-Fi in Point-to-Point (PtP) and Point-to-Multipoint (PtMP) scenarios, replacing wires in remote areas, or even in business and residential urban areas. Another likely scenario comprises one or more WiMAX Base Stations (BSs) providing access to several SSs connected through a mesh multi-hop network, extending WiMAX access coverage. This particular scenario is envisioned for urban residential areas.

Next, the fixed broadband access scenarios for rural (section 3.1.1.1) and urban (section 3.1.1.2) areas are presented.

3.1.1.1. Rural Broadband Wireless Access

Delivering high-quality, wireless broadband access to rural communities is a challenging WiMAX deployment scenario for both developed and developing countries. This is mainly due to the large distances between the remote area and the operator infrastructure. As a rule, the small number of potential subscribers in rural areas does not entice operators to put in place the wired infrastructure necessary for broadband access. Even in developed countries, it is not always cost-effective to deploy wired solutions and public sector subsidies are often necessary. In developing countries, it is simply not viable. Wired solutions, such as DSL or cable, are easily deployed only in areas with existing infrastructure. As a result, rural areas are often left uncovered contributing to the digital divide or are covered with bare bones connectivity. In this case, the WiMAX technology, particularly fixed WiMAX, can prove instrumental for providing broadband wireless access over large distances.

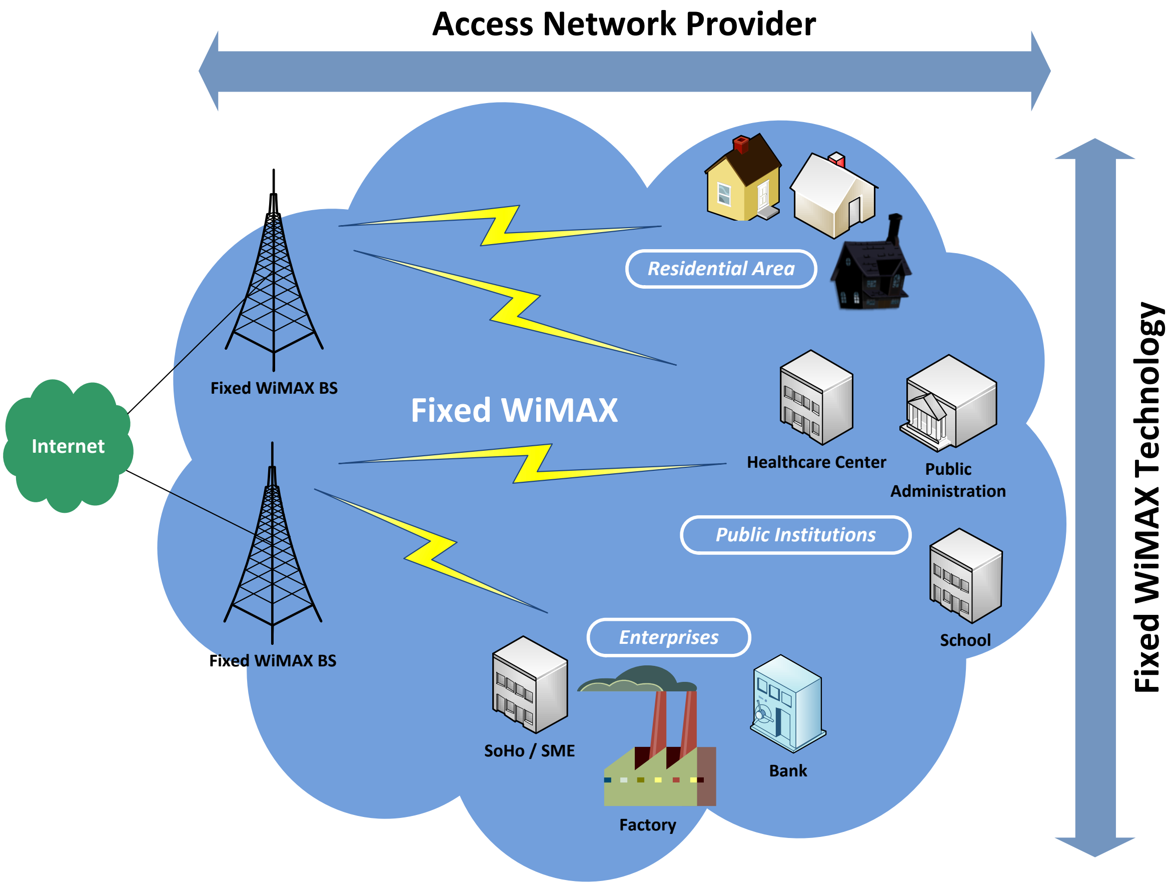

Figure 3-1: Rural PtMP fixed WiMAX access

Figure 3-1 illustrates a typical rural access connectivity scenario using fixed WiMAX technology. One or more WiMAX BSs are connected to the operator Core Network (CN) and provide wireless broadband connectivity to the rural area. Several WiMAX SSs, connected to the WiMAX BSs, are distributed over the remote area, including public institutions, residential areas, enterprises and healthcare centers, in a PtMP topology.

In these areas, nomadic scenarios are also an interesting application that can benefit WiMAX-based wireless access subscribers. The user can take his indoor WIMAX SS to another place and connect automatically to the WiMAX BS without requiring any technical support or contact between the customer and the network operator. For example, during a temporary construction, a company can benefit from the nomadic capability provided by WiMAX, connecting the construction head-office to the construction site temporarily, without having to subscribe for another access with the network provider. This is simply impossible with all other types of wired access technologies, broadband or not.

As mentioned above, fixed WiMAX can deliver capacities in the order of 10 Mbps with link spans that have publicly demonstrated to exceed 20 km in LOS conditions as presented later in this chapter. Application-level throughput depends on the network capacity, the channel bandwidth allocated and how sectors are defined. Operators can fine tune deployment details according to the subscriber population size and distribution using small angles to reach points farther away, or wider angles to distribute the available bandwidth among different customers.

WiMAX can also be used to establish connectivity between certain key points in the infrastructure and backhaul traffic from Local Access Networks (LANs). Later in this chapter, it is presented, for example, how WiMAX can be used to backhaul environmental monitoring data and audio/video streams from remote areas. In a similar fashion, WiMAX can connect a remote village with the closest operator infrastructure connection point. Inside the village, residents can connect using a local wireless Access Network (AN), as illustrated in Figure 3-2. In this scenario, the WiMAX SS is located in a central building, such as the town library, community center, or an administrative building. The WiMAX SS acts either as a network router (layer 3 device) or a layer 2 bridge/switch and provides local access to a range of qualified Wi-Fi connected devices [119]. Users do not have to purchase WiMAX-enabled devices or cards: they access the network using inexpensive, often integrated, and in general widely available Wi-Fi cards [120] [121].

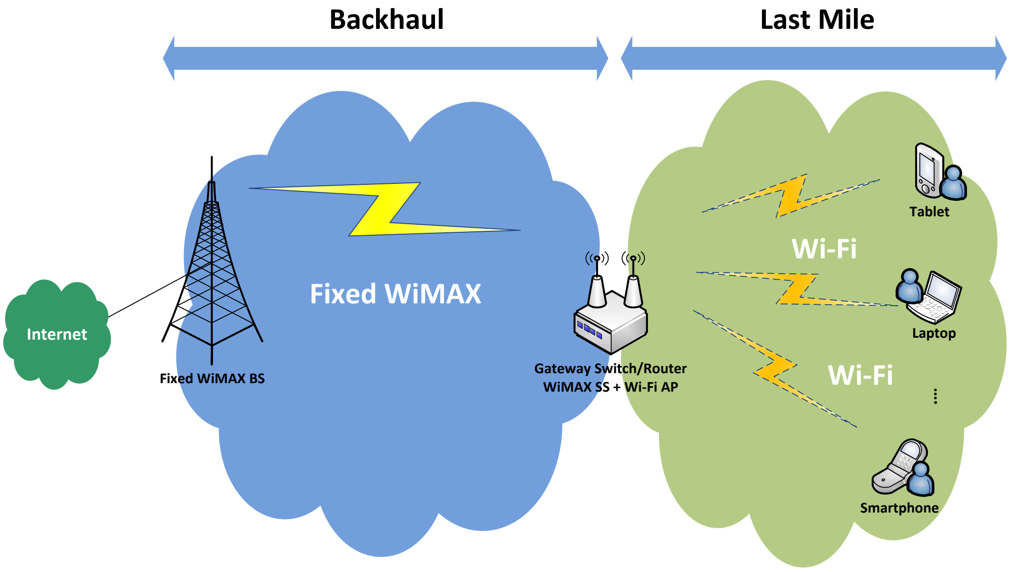

Figure 3-2: WiMAX backhaul for Wi-Fi

The WiMAX SS does not have to be collocated with the Wi-Fi Access Point (AP). Instead, it can be connected with a commodity Ethernet switch to a set of Wi-Fi APs, which can provide access to public buildings such as the village school and the local police station, as well as to residents in a common area, such as the town square or a city park. This kind of deployment could be subsidized, initiated and managed by, for example, the local community. Alternatively, a commercial network operator could deploy the WiMAX SS and then use local wireless area networks to reach potential customers, avoiding the installation of the entire cable infrastructure.

Another possibility is to actually install a Digital Subscriber Line Access Multiplexer (DSLAM) in the village and use the existing copper infrastructure for regular phone lines to provide xDSL services to residents and small business alike. This is illustrated in Figure 3-3, where the extension of the network is achieved, not by Wireless Local Area Networks (WLANs) but by copper lines. A network operator can then offer services in a harmonized way with the rest of the offerings in the area or the country. The WiMAX backhaul will be transparent from the user’s perspective, as a wired equivalent backhaul would be as well.

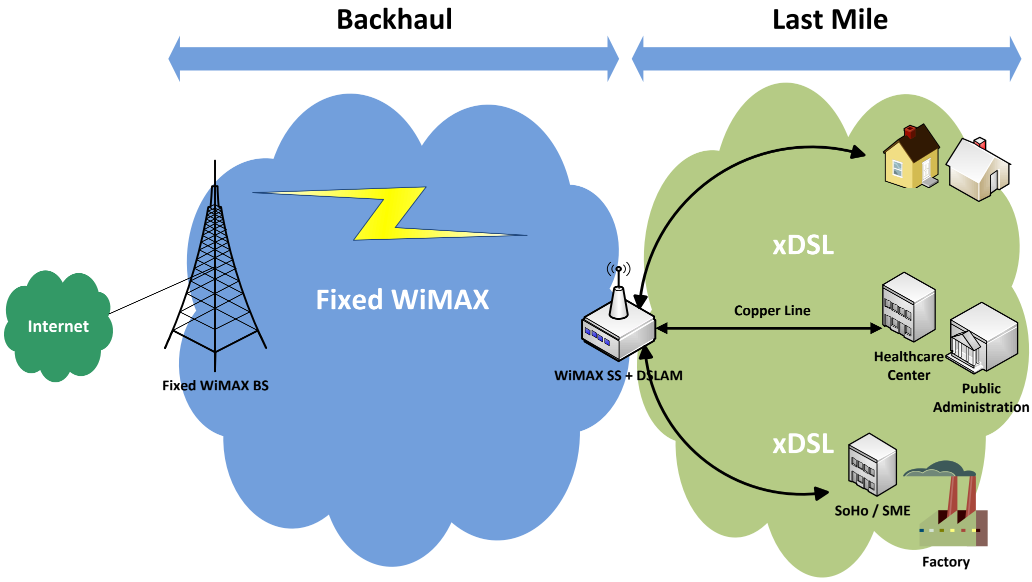

Figure 3-3: WiMAX backhaul for xDSL/Ethernet

Although the nominal capacity of the WLAN is considerably higher than the nominal capacity of typical fixed WiMAX COTS equipment, in practice it is more than sufficient [122]. First, fixed WiMAX operators can establish policies at the gateway router limiting the reservations for specific Wi-Fi APs and thus making sure that customers receive the service level that they have signed up for. Second, fixed WiMAX has been shown in the lab to be more reliable and stable in performance than COTS Wi-Fi access routers [123]. The central scheduling performed by the WiMAX BS and IP-level policing are sufficient to enforce proper sharing of resources. Third, the WiMAX uplink and downlink are controlled independently, and traffic in one direction does not affect traffic in the other.

Finally, and beyond generic Internet data traffic backhauling, there have been proposals to use WiMAX to backhaul cellular data and voice traffic. The inherent QoS capabilities of WiMAX can meet the stringent requirements of cellular communication. The larger one-way delay is a concern, but for remote areas WiMAX can provide an acceptable price/performance trade-off [122] [123]. Telecommunications operators have long been using proprietary microwave links to connect different offices or points of presence. Adopting a standard microwave solution such as WiMAX cannot be considered far-fetched.

3.1.1.2. Urban Broadband Wireless Access

Although remote areas are very demanding to cover due to natural terrain challenges, urban zones are in fact one of the most difficult areas to provide truly cost-effective broadband connectivity. Mainly due to the large number of buildings, it is expensive and time consuming to deploy a wired broadband solution such as xDSL or cable in these environments. Furthermore, cities with old or inadequate infrastructures are not encouraging network operators to install a wired solution. Historic, traditional and under preservation buildings also need network coverage, but cannot always be wired.

Fixed WiMAX is a very attractive solution to overcome the demanding challenges posed by urban areas. It is easy and very fast to install, without requiring major construction effort or structural interventions in buildings. Consequently, WiMAX proves to be significantly more cost effective when compared with wired alternatives and can deal with all types of physical environments, including NLOS conditions.

A typical urban scenario using fixed WiMAX as the access technology is shown in Figure 3-4. Potential subscribers, which may be interested in this type of deployment, include residential customers, small and big enterprises, university campuses, public institutions and hospitals. Providing connectivity between the operator network and the customer is often straightforward. It simply requires the installation of a WiMAX SS inside the target building(s) or, in the worst-case scenario, on the roof of the target building(s) to obtain higher throughputs.

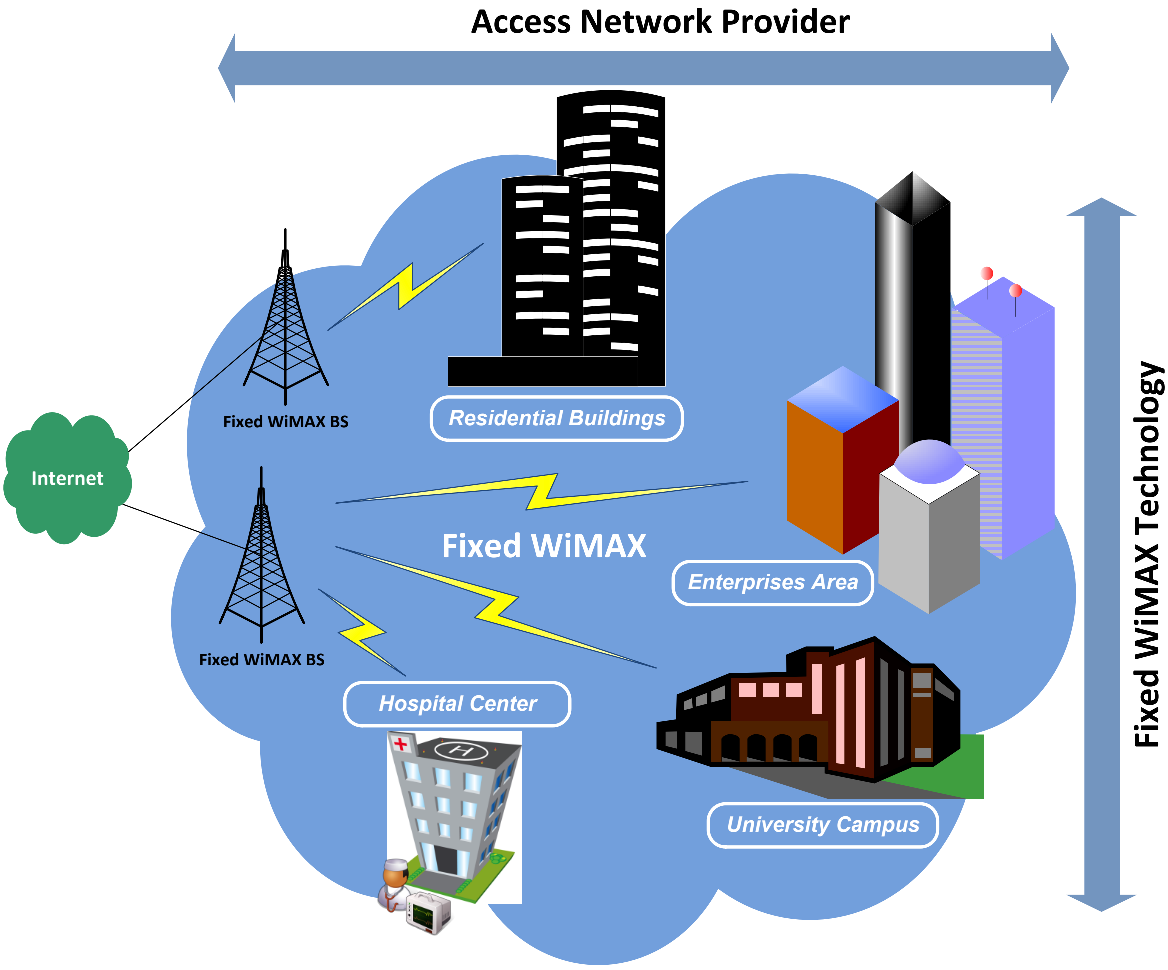

Figure 3-4: Urban PtMP fixed WiMAX access

To address the radio signal propagation challenges mainly posed by tall buildings, the scenario depicted in Figure 3-5 includes a WiMAX relay system, based on the IEEE 802.16j standard [118]. IEEE 802.16j will enhance WiMAX with the capability to provide Mobile Multi-hop Relay (MMR) by introducing Relay Stations (RSs) between the WiMAX BS and the receiving nodes. As a result, the WiMAX BS cell coverage can be significantly extended. Furthermore, the 802.16j specification guarantees that the receiving entities will not notice the existence of WiMAX RSs in the path towards the WiMAX BS, i.e., it is completely transparent to the terminal.

Based on the WiMAX RS capabilities, the MMR systems can operate in two distinct modes, namely, transparent or non-transparent. In transparent mode, the transparent RSs, also referred to simple RS, are only capable to process and forward data traffic, whereas the signaling messages, such as the MAC management messages, must be sent towards the controlling BS (or master BS). In non-transparent mode, the non-transparent RS has the capacity to forward both signaling and data traffic towards the final nodes. Therefore, the non-transparent RSs are able to locally manage and control the WiMAX link, without synchronizing with the master BS.

A WiMAX mesh topology is also depicted, illustrated by the red thunders in Figure 3-5, allowing the direct communication between the WiMAX SSs installed on the buildings. Combining both mesh and MMR capabilities, fixed WiMAX is able to meet the challenges posed by the urban landscape. In this scenario, a WiMAX operator can provide broadband access, overcoming NLOS conditions and optimizing traffic routing by directly connecting different SSs.

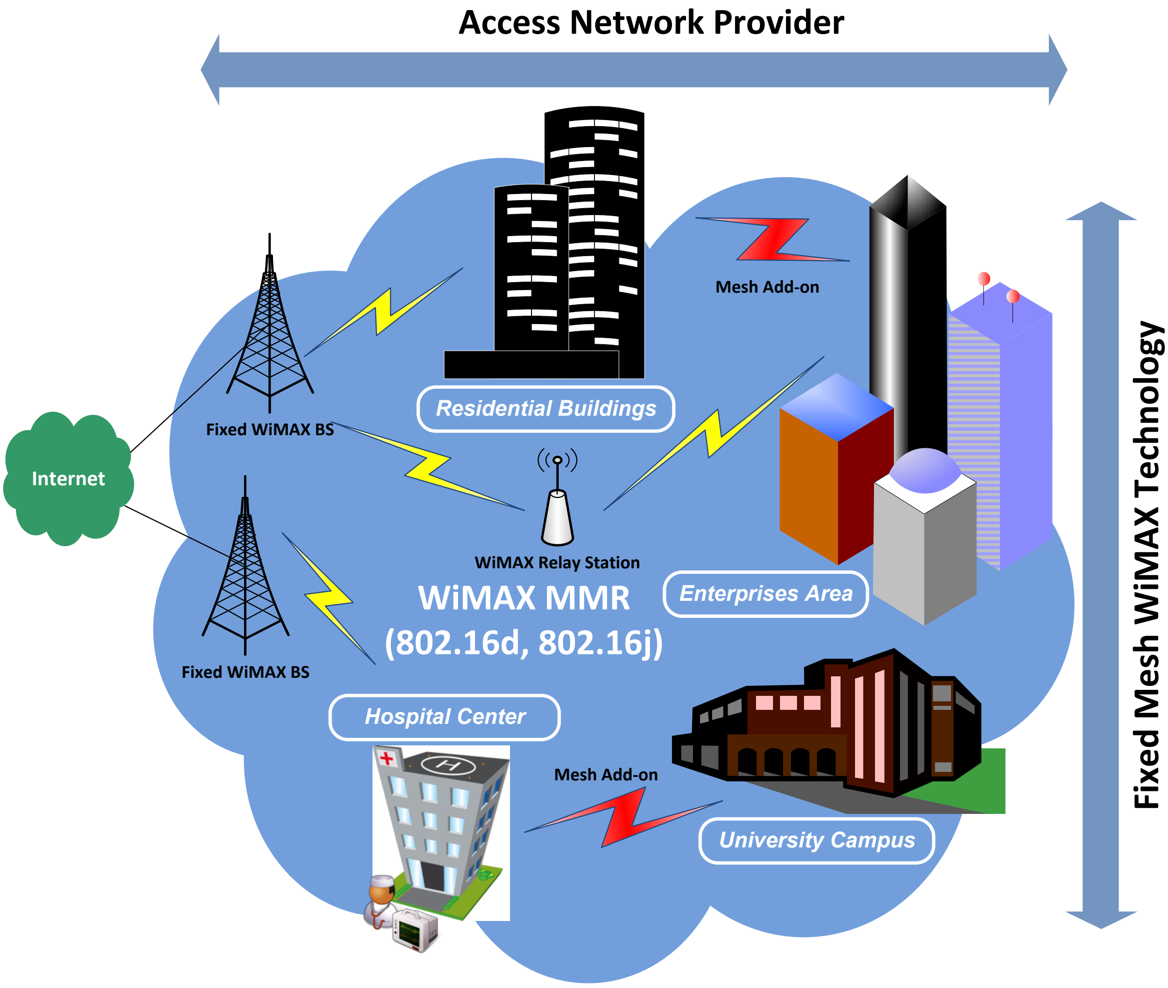

Figure 3-5: Urban PtMP fixed WiMAX MMR access (with mesh add-on)

3.1.2. Mobile Broadband Wireless Access

Presently, wireless telecom operators are seeking for next generation access technologies, capable of integrating all-IP architectures, with QoS support and high throughputs, as well as seamless mobility mechanisms. Users of next generation wireless networks will look for a combination of services that are currently offered in fixed environments, such as VoIP, video streaming and data communications, with their mobile life style, enabling more futuristic application scenarios [124] [125] [126]. The following subsections present a group of mobile broadband wireless scenarios, focused on local and metropolitan broadband wireless access (section 3.1.2.1) and inter-technology seamless mobility.

3.1.2.1. Local and Metropolitan Mobile Broadband Wireless Access

LTE and WiMAX are built upon an all-IP framework, able to deliver triple-play services with QoS support to mobile terminals. Bearing in mind these unique features, one of the most interesting scenarios for next generation wireless ANs is to provide broadband connectivity to mobile users using multi-access radio technologies. Users will be able to access broadband wireless Internet using different devices, such as smartphones, laptops and/or tablets, through MANs (LTE, WiMAX) and LANs (e.g. Wi-Fi).

Figure 3-6 illustrates a mobile broadband access scenario comprising metropolitan wireless ANs, such as WiMAX – IEEE 802.16e and IEEE 802.16m versions, LTE and LTE-Advanced, as well as Wi-Fi for local wireless ANs.

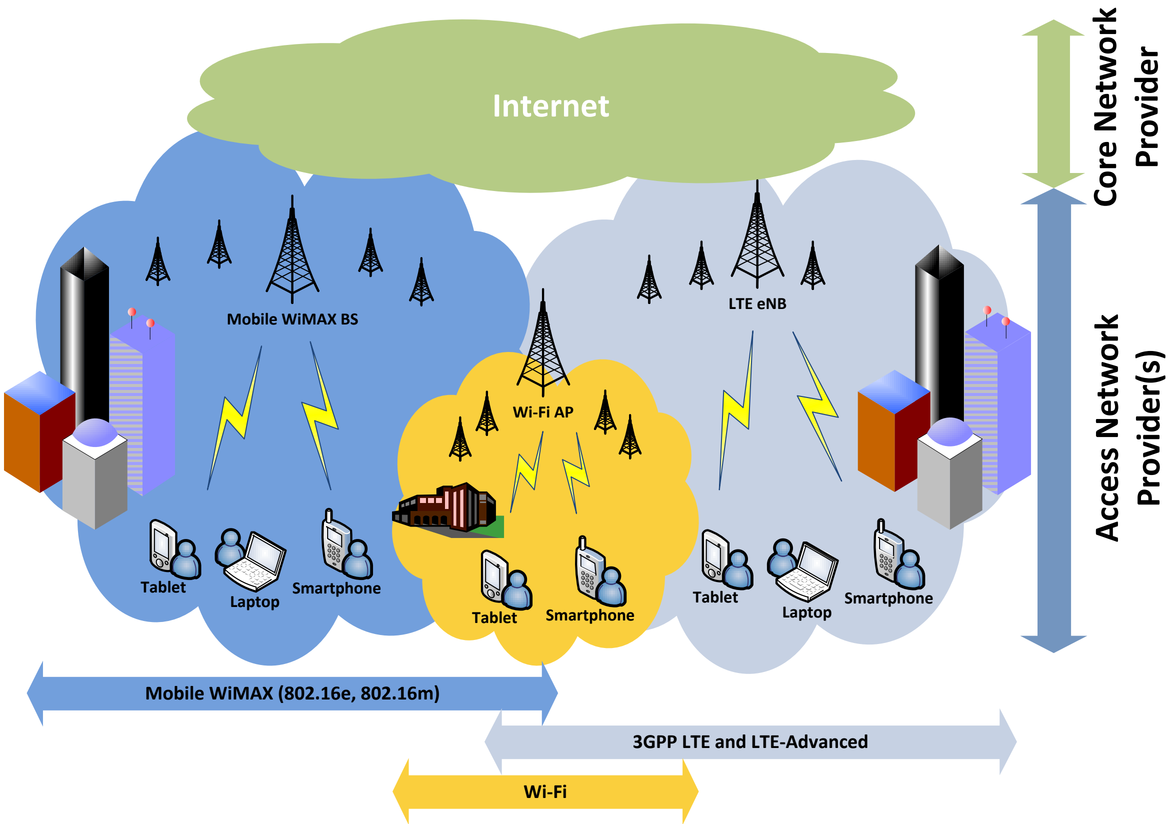

Figure 3-6: Local and metropolitan mobile BWA scenario

3.1.2.2. Inter-Technology Seamless Mobility

Nowadays users are always in range of at least a UMTS/HSPA cell, a WiMAX BS or a Wi-Fi hotspot. With networks supporting vertical handovers, terminals can move or be moved between these networks without losing connectivity or interrupting active services. Not only this allows users to move freely without any concerns of "being in cell range" but it also allows for dynamic network selection. Vertical handover is very little intrusive and does not require the confirmation of acceptance by the user whenever the terminal moves from a network to another. It propitiates seamless mobility and reduces the awareness required by users to respond and interact with the network and allows him to concentrate on the services at hand. Another clear advantage is that vertical handover also permits superior network selection adequate to the services and quality required by the user. Whenever the current network does not allow for a certain service to be provided with QoS, users are moved to one that can, either by reasons such as signal degradation, overloaded cells or networks, low bandwidth availability or even cost efficiency.

Operators are constantly searching for new ways of attracting clients to their networks and services. Vertical handover not only extends the availability of new and better services, but also permits a better QoS and makes them more attractive to users. Enabled clients will also be more satisfied with the less service interruption and the improved operator coverage. These operators can integrate their various systems as one multi AN with combined covered areas. This is advantageous for users and also for operators that will not require covering all terrain, especially the less profitable locations, with all their network technologies. Vertical handover also presents itself as an exceptional way to promote and introduce new network technologies. It allows the balance of networks traffic between the available systems and users between the accessible cells. This improves the efficiency of the networks and the quality of the services available to users. Operators possessing several network technologies can combine them in this way to increase their own strength and users fidelity. Smaller operators can establish partnerships to gain access to new access systems and increase their service offers.

For telecommunication regulators, vertical handover represents an opportunity to promote the market competition. Smaller operators will be able to specialize in specific services while benefiting from partnerships to promote their networks. Content providers will also find new and efficient forms of delivering their services. Users will be allowed to choose networks more effectively and based on quality and price factors. In most cases they will be paying for the optimal service and not only for an available one.

3.1.2.2.1 Coping with Imminent Network Unavailability

This scenario ensures that the user is always connected to the Internet, wherever there are access networks available. Thus, if the connection to a specific AN starts degrading and it is predictable that it will become inaccessible (e.g. when the user moves around and the connection to the Wi-Fi wireless network is lost), the user is automatically connected to the best available wireless AN (e.g. UMTS/HSPA, LTE, WiMAX) in the MN range.

A possible use-case example for this scenario is illustrated in Figure 3-7. A mobile broadband user, in this case a university professor, is in his office, located on the university campus, watching a live video stream in his multi-access tablet through the Wi-Fi local wireless network. Meanwhile the professor decides to leave the office and take a taxi for a meeting in an enterprise in the city center. From a connectivity perspective, when the professor leaves the university, its MN, in this case the multi-access tablet PC, looses connectivity to the Wi-Fi network. Since both LTE and WiMAX access technologies are available on the metropolitan area, the tablet PC detects these broadband wireless networks and automatically performs the vertical handover from the Wi-Fi AN to the LTE or WiMAX AN. This procedure is made without the professor detecting any handover procedures and, therefore, abstracting all connectivity details from the user. From the video application perspective, the consumer does not notice any traffic disruption on the live video stream.

This scenario enables the network operator to provide a novel service to its customers and simultaneously improves the service delivery quality; from the client point of view, it provides a seamless connectivity experience without traffic disruption.

Figure 3-7 illustrates the Wi-Fi to LTE or WiMAX seamless handover (from the left to the right) motivated by imminent network unavailability.

3.1.2.2.2 Access Technologies Resources Optimization

This scenario refers to those where the main motivation to performing handover is related with radio resources optimization. These cases are tied to load balancing users and services around the available ANs. It is based on the information from both the terminal and network side added to some predictability of user habits on different areas and times of the day.

Given the increasing shortage of resources in 3G broadband ANs and the proliferation of Wi-Fi hotspots, automatic offloading of 3G allows operators to optimize the radio resources of these networks and, simultaneously, to make the most of their Wi-Fi hotspots. The 3G offload demands for seamless handover procedures between both access technologies. From the mobile operator perspective, due to the huge video traffic growth in the last two years and the expected exponential growth in the coming years, mostly motivated by the smartphones explosion, a strong "pressure" on the operators' 3G HSPA networks is already taking place. Therefore, it is important to have the required mechanisms in place to handover users from 3G to Wi-Fi networks seamlessly, thereby offloading the 3G HSPA network in locations with Wi-Fi coverage.

A possible use-case example for this scenario is the following: a mobile broadband user, in this case a university student, is traveling to the university using the bus. During his trip he decides to watch a live broadcast TV channel in his multi-access tablet PC. As a result, the terminal automatically connects to the LTE or WiMAX MANs. Meanwhile the student leaves the bus and walks through the university campus. As soon as the Wi-Fi network is detected by the student tablet PC, the live broadcast TV channel is handed over to the local Wi-Fi network, releasing the radio resources that were being used. As in the previous scenario, the handover from LTE or WiMAX to Wi-Fi is achieved without any perception from the user and without traffic disruption.

From the network operator perspective, this scenario has the following advantages:

- Monetization of the Wi-Fi infrastructure;

- Optimization of radio resources – in this particular scenario resources from the wireless metropolitan access networks (LTE or WiMAX) are released;
- Differentiation from competing network operators.

On the other hand, from the user point of view, it enables the following:

- Session continuity;
- QoS adaptation;
- Service cost – Wi-Fi is usually less expensive for the user.

Figure 3-7 illustrates the foreseen network resources optimization scenario – seamless handover from LTE or WiMAX to Wi-Fi (from right to left).

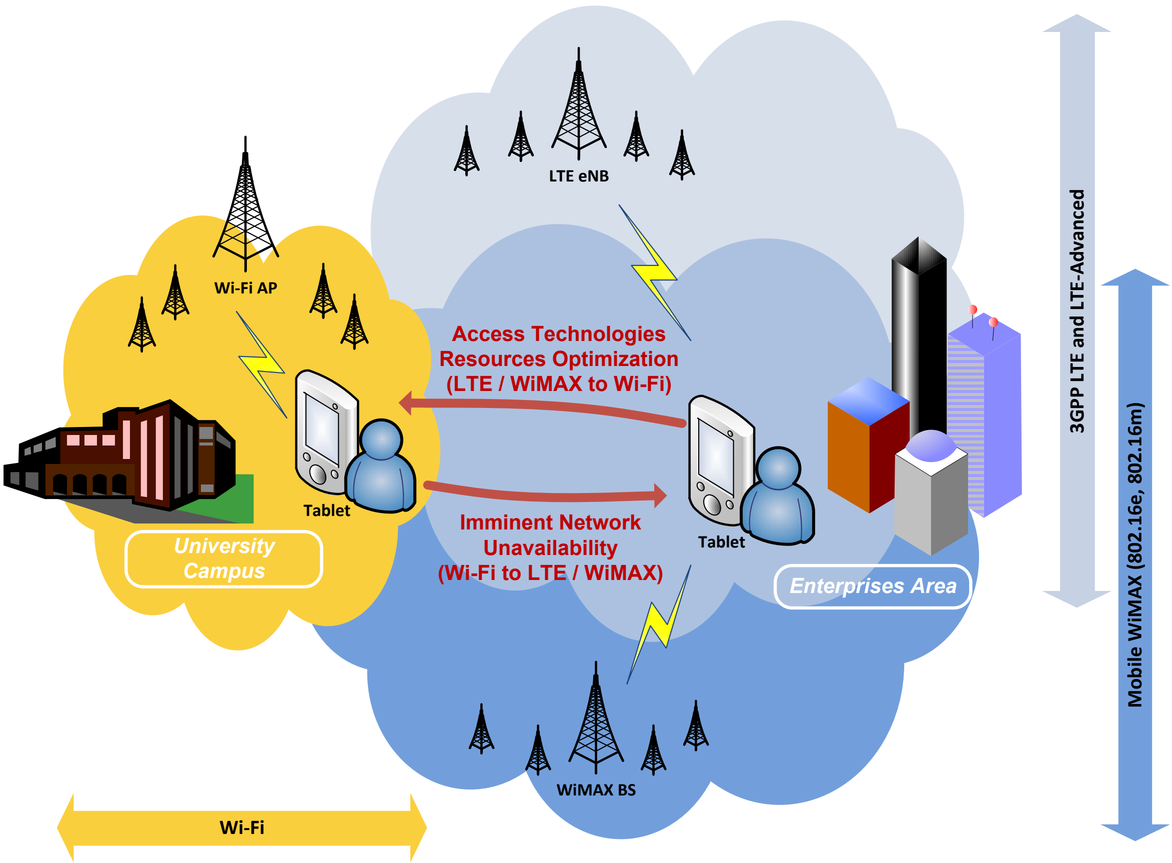

Figure 3-7: Inter-technology seamless mobility scenarios

Next, based on what was presented in this section, it is explained how the WiMAX and LTE broadband wireless access technologies can also be used for telemedicine applications, on-site ambulance and accident monitoring, and environmental monitoring applications. All these often require surveillance of remote and/or otherwise inaccessible locations. For example, it is described how WiMAX and LTE can be employed in emergency and high-mobility scenarios, as well as volcano monitoring and fire prevention applications.

3.2. Telemedicine Application Scenarios

E-health is one of the areas where broadband wireless access technologies can substantially contribute to improve the daily activities, and therefore, enhance the quality of life of the citizens. Today a large number of medical activities are carried out with limited success, unnecessary costs and human difficulties, because of the inability to exchange real time information between different elements of the chain that are not at fixed locations. Some of the possible advanced medical services that can benefit from the integration of a wireless broadband access technology are the following:

- Remote diagnosis: need to transmit urgent data in order to make an immediate basic diagnosis, e.g. street accidents, people in special health conditions (pace-maker bearers, pregnant women, to name a few);
- Need to intervene on non transportable patients (e.g. accidents) may require off-air transmission of critical data or images;
- Remote monitoring: today the elderly are remotely monitored when at home, but not when traveling or simply moving around town. This limits their ability to enjoy life and be integrated in the community around them;
- Remote follow-up: today patients travel to distant hospitals to be followed-up after therapies or chirurgical interventions.

3.2.1. Remote Patient Monitoring

During the last decade, the healthcare system has been giving much more attention to remote monitoring and assistance of patients. Remote patient monitoring poses hard challenges in order to give a differentiated support to each patient, creating a personalized follow-up plan, which depends on the patient illness. Furthermore, it is very important that a bidirectional, secure, reliable and trustworthy relationship between the patient and the healthcare provider is established, allowing the patient to proactively trigger the communication with the hospital and share important information or symptoms with the medical team. By the same token, the hospital doctors must also be able to remotely control and monitor the patient measurements, as well as send periodical reminders to the patient in order to take his medication (Figure 3-8).

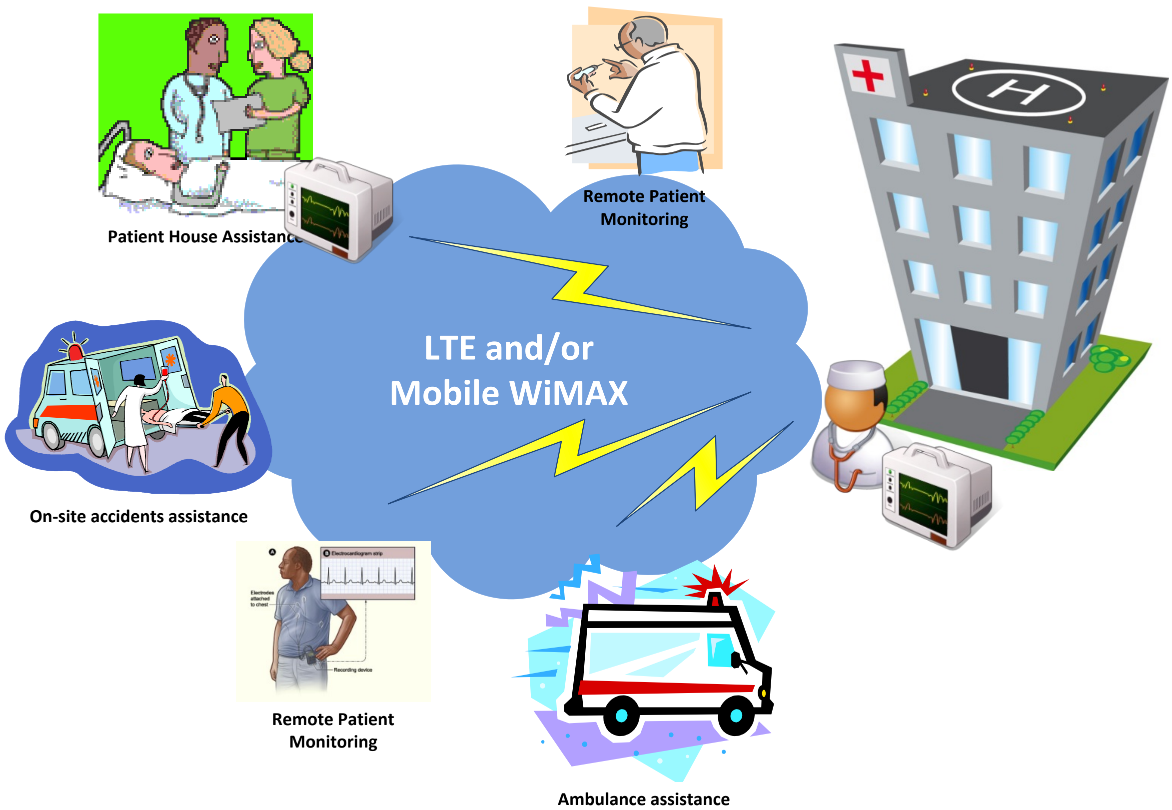

Figure 3-8: Remote patient monitoring

Another important category comprises patients with chronic diseases that can be remotely monitored during all day, without having to change their daily life routine. For instance, if the patient professional life demands a constant need to travel abroad, he can easily maintain his work routine. Keeping chronic patients physically away from the healthcare center, not only improves the patients' quality of life, but is also cost effective for healthcare institutions, saving in medical staff, as well as on the number of required beds.

Despite the benefits provided by the telemedicine applications, until this moment no access technology was able to fulfill its challenging requirements, namely, wireless broadband availability, including QoS differentiation, as well as intrinsic mobility support. WiMAX and/or LTE, as broadband wireless access technologies for metropolitan environments, are promising candidate technologies to overcome this gap and to allow both healthcare institutions and patients to benefit from this application, as illustrated in Figure 3-8 [128] [129] [130]. Here, the mobile version of WiMAX and/or the LTE access technology are employed, allowing patients to be remotely monitored by its healthcare institution.

3.2.2. On-site Medical Assistance

Another important scenario for telemedicine applications is to provide the remote medical staff with the capability to immediately establish a secure and reliable communication channel with the healthcare center. This scenario is also illustrated in Figure 3-8 (Patient House Assistance).

Using the WiMAX and/or LTE BWA technologies, when a doctor assists a patient at home (e.g. senior citizen, pregnant women, patient with a chronic illness), he can easily establish a reliable communication channel with the hospital and retrieve important information about the patient, as well as send the portable ultrasound device results to the hospital. It also allows the doctor to exchange information and ask for a second opinion to his colleagues from the hospital. Furthermore, if necessary, a video-conference session can be established in real time using the doctor laptop. If the doctor is visiting a pregnant woman, he can upload the ultrasound pictures from the baby to the hospital server and configure it to distribute the pictures to the father of the baby.

Another interesting scenario, also illustrated in Figure 3-8 (Ambulance Assistance), is when a doctor is on duty in an ambulance and is called to intervene on a car accident [131] [132]. The ambulance is equipped with a portable ultrasound device, connected to the broadband wireless access technology. An injured man is found and to allow the fastest possible intervention, while travelling towards the hospital, the doctor collects important information about the patient condition and sends it to his colleagues in the hospital. Based on this input, the medical staff can start preparing the first aids and the surgery, as well as share with the ambulance doctor important information about the patient.

3.3. Environmental Monitoring Application Scenarios

The WiMAX technology also fits very well into a large number of environmental monitoring applications, mainly due to its wide coverage potential in remote areas, and also as a result of its inherent support for broadband applications and QoS mechanisms. In this section, two environmental monitoring application areas are presented: monitoring of seismic and volcanic activity, as well as fire prevention [133] [134].

3.3.1. Seismic Activity

Europe has several regions with high seismic activity, requiring permanent monitoring in order to prevent calamity situations. The main affected regions are in the south, due to the fault zone between the Euro-Asian and African plates, and in the north, due to the fault zone between the Euro-Asian and North-America plates. This section describes typical seismic activity scenarios and presents the main challenges associated with volcano monitoring, which relies strongly on the observation of seismic activity patterns.

3.3.1.1. Seismic Activity Monitoring

The monitoring of seismic activity plays a critical role on the minimization of the impact of its effects on populations and facilities. The effect of seismic activities, also referred as earthquakes, have a direct impact on the ground shaking and rupture, causing damage to service structures, such as dams and bridges, but can also be responsible for other non-exclusive natural disasters such as fires, tsunamis and floods.

Therefore, the detection or even prediction of seismic activities is critical for the planning of preventive actions, as well as for all the remedial actions to be carried out during and after such occurrences.

Nowadays, there are several sensor networks deployed in critical regions, dedicated to the collection of seismic signals. Usually, the information is stored in local storage devices and regularly sent to the acquisition center. However, the continuous and real-time transmission of data to the acquisition center would improve the reaction time in situations of crisis. In this context, fixed WiMAX technology introduces an added value, due to its broadband capabilities over long distances. Namely, by providing, in real-time, data of seismic sensors from different sources, many located in places distant over 30 km, the prediction of earthquakes may become more efficient and focused.

3.3.1.2. Volcano Monitoring

From the different events associated with seismic activity, volcano eruption is one of the most feared, especially in places with a long history of volcano activity, such as Iceland, Italy and Portugal. It is therefore critical an increased coverage to monitor the seismic activity associated with volcanic activities. This is even more important, given that seismic activity preceding volcano eruption are only observed approximately one hour before the magma reaches the surface. With such a hard constraint, real-time transmission of data is vital for the early warning and preparation for the oncoming risk.

Besides relying on seismic activity observation, volcano monitoring is complemented by the use of gas monitoring equipment, which is located close to the peak of the volcano. Additionally, video surveillance cameras are placed in mountains around the volcano in order to expose the location of the eruptive site and to follow the ascension of the volcanic column into the upper atmosphere.

In this scenario, wired technologies are naturally inappropriate, and most wireless technologies do not fulfill the connectivity at long distances with high bandwidth. Moreover, the access to the seismic and gas monitoring sensors, as well as to the video surveillance cameras can benefit from communication both with LOS and NLOS. Therefore, the use of fixed WiMAX as a BWA technology becomes appealing and a strong candidate to fulfill the communication requirements of such demanding scenarios.

In addition to being an important contribution for the successful deployment of the application scenarios described above, mobile broadband technologies, such as mobile WiMAX and LTE also brings benefits to the field personnel who installs and maintains the monitoring equipment, as well as to the civil protection personnel and rescue teams in disaster situations. Namely, the wireless broadband access with mobility features allows for a real time communication between the personnel and the acquisition center, as well as with emergency services.

3.3.2. Fire Prevention

For Southern European countries – such as Portugal, Spain, Greece and southern France – forest fires represent a dramatic loss of lives and property, as well as an increased risk of desertification and the higher emissions of greenhouse gases. The same applies, to some extent, to some areas of the United States, Australia and other countries. In order to address this situation, considerable public investment has been made in fire prevention (e.g. proactive land management and preventive clearing of ground vegetation), fire detection networks (surveillance posts, aerial patrols, car patrols, semi-automated fire detection mechanisms) and fire fighting resources (aerial resources, firefighting vehicles, firefighters and civil protection personnel, etc.). Nevertheless, due to climatic factors, increased desertification and land usage practices, these efforts remain largely unsuccessful.

3.3.2.1. Fire Detection

One of the key success factors in this area of environmental monitoring is early fire detection, since an unattended fire ignition may evolve – with favorable weather conditions – to uncontrollable proportions in less than an hour. However, forest areas are typically scarcely populated and difficult to reach. In these areas, fire detection is traditionally performed by human spotters – on the top of surveillance towers or, in some cases, small airplanes – searching for smoke signals and communicating their findings to centralized control centers. These methods are not cost-efficient: each tower requires the permanent presence of human watchers. Moreover, verbal radio communication can be ineffective as the control center loses precious minutes processing the spotter description and attempting to locate the potential fire precisely, before dispatching an airborne first response team. A small country such as Portugal, for instance, needs to keep a network of more than 230 surveillance towers, just to get basic coverage of fire-sensitive territories.

Electronic surveillance mechanisms (for instance video surveillance with automatic detection of smoke or heat sources) are not fully autonomous, since human confirmation of potential fires is always required. Nevertheless, they do improve the efficiency of surveillance networks:

- Personnel costs are greatly reduced. Even with plain simple remote video surveillance, one centrally located operator can easily manage multiple surveillance towers;
- Fire location becomes faster and more precise, due to automated triangulation between adjacent surveillance towers and association with Geographic Information Systems (GIS);
- False alarms are easier to identify. Instead of relying in verbal descriptions from remote human spotters, the centralized operator can have simultaneous access to the video and data gathered at each surveillance tower that covers the potential fire location. The decision process becomes faster and more precise, leading to reduced costs with unnecessary dispatches of helicopter crews;
- Electronic surveillance can operate continuously, unlike traditional surveillance networks which, due to their high costs, are usually limited to few months per year, despite the fact that recent climatic changes increase the frequency of violent off-season fires;
- Recorded data has great forensic value for criminal investigation and scientific research.

Video is the basis of electronic fire surveillance. Plain video surveillance already provides very positive results, and more sophisticated tools can be easily added for automated detection of smoke of heat sources. Other data, such as local meteorological data and digital compasses, play an important role during the detection and monitoring phases, but video is usually the key component (and also the most bandwidth demanding one).

One of the major shortcomings of electronic surveillance is communication between surveillance towers and control centers. Broadband access technologies such as xDSL or 3G are unavailable in remote forests, and alternatives such as General Packet Radio Service (GPRS), GSM or Ultra-High Frequency (UHF) radio-links, besides also presenting coverage limitations, rarely provide the bandwidth required for effective electronic monitoring. Fixed WiMAX technology fits well in this scenario. Given its potential range, bandwidth and adaptability to environmental conditions, WiMAX may provide connectivity to remote monitoring systems, capable of effectively providing early detection of fire in a more efficient and cost-effective manner.

3.3.2.2. Fire Monitoring and Firefight Coordination

Electronic surveillance is also critical during the fire-fighting phase. Senior coordinators, located at the operations control centers, can see by themselves the live evolution of the fire, often from multiple angles. Once again, this is a tremendous advantage over making strategic decisions based on verbal information received from remote watchers and firefighters.

At another level, BWA technologies may also play an important role in the coordination of partners involved in the firefight, for instance allowing the instant exchange of data between firefighters and the control center (such as status and GPS-location of the firefighter vehicles, meteorological data, GIS data, video and images of the fire gathered at multiple locations, instructions from the control center, etc.). This is not much different from classical warfare scenarios, where increased access to shared intelligence improves the global capacity of the military team.

It should be noted, however, that the requirements for electronic surveillance and firefight coordination are different. Electronic surveillance is based on a limited number of fixed network nodes (the surveillance towers), with very large distances between them but usually with LOS conditions, due to their placement in strategically high locations. Fixed WiMAX networks, with PtP or PtMP links, provide a satisfactory answer in this case. Firefight coordination, in the other hand, requires support for mobile or nomadic terminals. Distances involved are potentially smaller, but the location of each network node is sub-optimal (e.g. vehicles in valleys and ravines without line of sight), imposing more demanding coverage problems. In this context mobile WiMAX and/or LTE are more adequate.

3.3.2.3. A WiMAX Testbed for Electronic Fire Surveillance

In order to assess the suitability of WiMAX for the already discussed fire prevention scenario, a fixed WiMAX-compliant testbed was set up in Coimbra, in conjunction between PTIN and University of Coimbra. The installation, configuration and management of the WiMAX system was made under the scope of this Thesis, whereas the surveillance cameras and the remote surveillance application was developed by University of Coimbra.

The testbed included two fire surveillance towers (located in the Lousã and Carvalho mountains) already in use by regional fire prevention services. Each of these towers is now equipped with surveillance cameras, digital compasses for geographical location of detected fires, and weather stations (wind, temperature, humidity) [135].

For the WiMAX testbed mount preparation, several places were visited to find a suitable place for the WiMAX antennas installation. Some of the requirements for WiMAX system installation were a high position spot with clear view over a large area, availability of electrical energy and the existence of an infrastructure to protect the equipment from adverse weather conditions or from vandalism acts. Three candidate sites were identified: Lousã Mountain (LM), Carvalho Mountain (CM) and University of Coimbra (UC) regarding the constraints exposed above. Using simulation results and geographical data, the radio links between UC – LM, LM – CM and UC – CM were evaluated. Figure 3-9, Figure 3-10 and Figure 3-11 describe the terrain profiles and the Fresnel ellipsoids considering 66% and 90% of clearance.

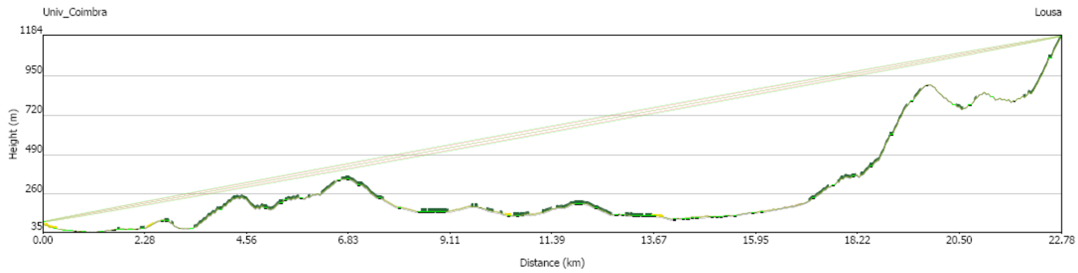

Figure 3-9: UC – LM terrain profile

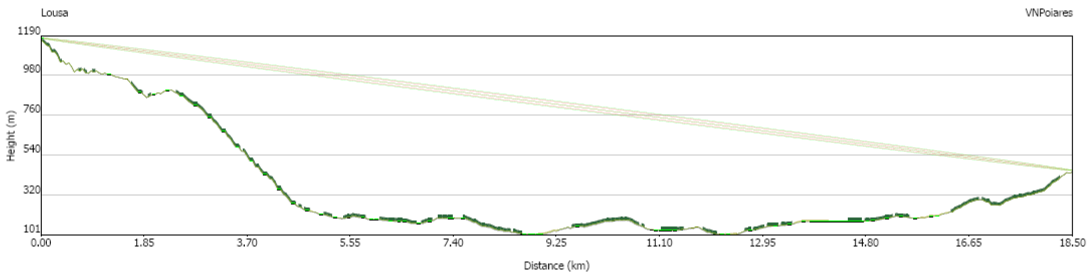

Figure 3-10: LM – CM terrain profile

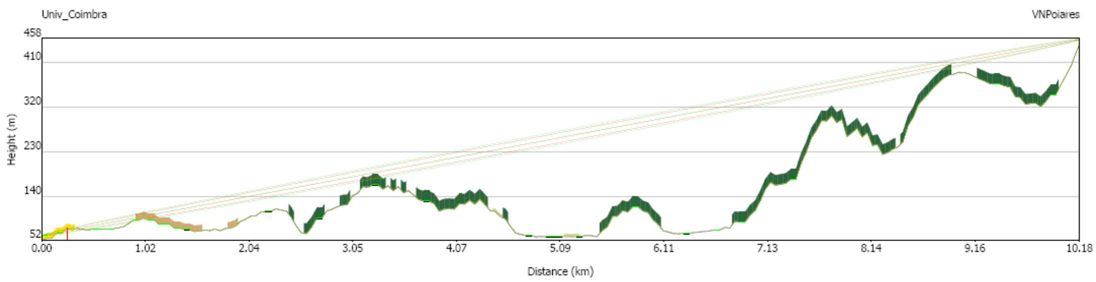

Figure 3-11: UC – CM terrain profile

Due to very difficult propagation condition (NLOS in a forest environment without a terrain topological place, like a mountain, to be used as reflection surface), it was not expectable that a radio link between UC

– CM could be established. Therefore, the PtMP network topology with the WiMAX BS on UC and the WiMAX SSs on CM and LM was abandoned. A new network topology with two PtP links, one between UC – LM (also known as *Aggregation_Link*) and the other one between LM – CM (also known as *Single_Cam_Link*) has been implemented, using different frequencies on the radio link in order to minimize interference. Figure 3-12 depicts the three antennas location and the link propagation conditions.

Figure 3-12: Fire prevention WiMAX testbed antennas location

A more detailed illustration of the WiMAX testbed is presented in Figure 3-13. A 24 km WiMAX link connects UC with the first surveillance unit at the LM. A second WiMAX link connects CM with LM (19 km), further stretching WiMAX coverage into the remote forest. Both links are PtMP (making it possible to add further surveillance units, in the future), and neither of these towers has alternative broadband coverage (xDSL, 3G…).

The remote surveillance application is composed of remote surveillance units, a central application server and web clients that can be installed in laptops, desktop PCs or tablets. Each remote surveillance unit consists of one or several outdoor cameras controlled by an IP video server, IP compasses and an IP weather station (temperature, wind, humidity). The cameras automatically scan pre-defined sections of the forest and stream the video to the remote client. When the user detects a potential fire, he points the camera to the suspected location (performing remote rotation, tilt and zoom), in order to conduct a more detailed inspection. If the alarm is confirmed, the digital compass is used to determine the exact location of the fire and an early response fire brigade is sent to the location, by helicopter. Figure 3-14 illustrates the remote video surveillance application.

Each one of the remote surveillance units provides effective coverage in a radius of approximately 10 km from LM and from CM. The central server is located at the UC, and client PCs can be located anywhere in the Internet. The surveillance units were installed in watchtowers where the Civil Protection already keeps human watchers during the summer, equipped with binoculars. It will be possible, therefore, to directly compare the performance of classic fire detection mechanisms and remote video surveillance. The key metric is the ability to early detect the fire, since the success of fire fighters greatly depends on the ability to reach the fire location within minutes from ignition, before it becomes uncontrollable. If the remote surveillance proves to be at least as effective as classic surveillance, it will be possible to reduce labor costs (a single operator can control several surveillance units) and to increase the number of surveillance posts, thus further increasing the probability of successful fire detection.

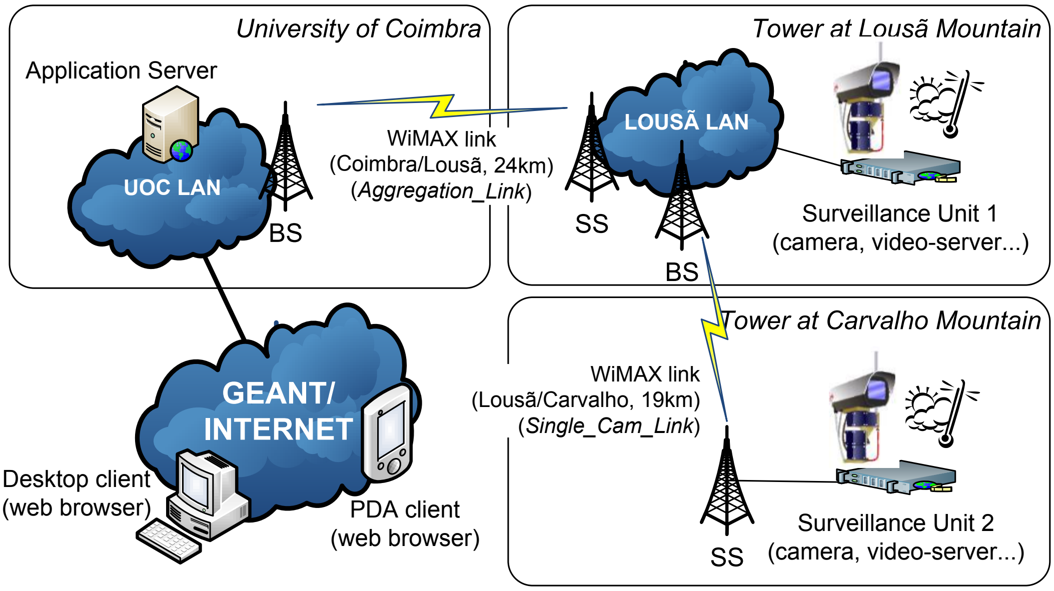

Figure 3-13: Fire prevention WiMAX testbed topology

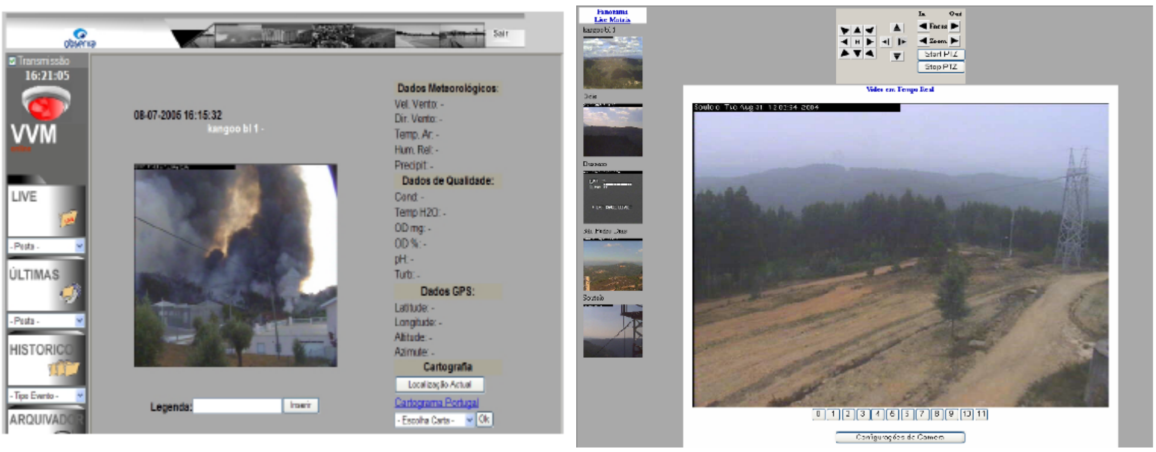

Figure 3-14: Fire prevention remote surveillance application

The system is operating in the 3443-3471 MHz frequency range for the *Aggregation_Link* and on the 3543-3571 MHz interval for the *Single_Cam_Link*. Detailed information about the WiMAX equipments configuration is presented in Table 3-1.

Table 3-1: Fire prevention WiMAX testbed equipments configuration

BS / SS, Location	BW (MHz)	Power (dBm)	Antenna
BS, UC	3.5, 7 and 14	23	90º
SS, LM		16	15º
BS, LM		23	90º
SS, CM		16	15º

In order to study the performance of the installed testbed, a set of measurements were made for the two WiMAX links – *Aggregation_Link* between UC and LM, and the *SingleCam_Link* between LM and CM. The aim of these measurements was to verify if the installed WiMAX links were able to fulfill the fire prevention video application bandwidth requirements – cameras will stream video with 1.5 Mbps.

It is important to differentiate between the two radio links. Although both of them have LOS propagation conditions, the distance for the *Aggregation_Link* is larger than the *SingleCam_Link* (Table 3-1). Moreover, since the *Aggregation_Link* is the "*aggregation link*" of the testbed, it has to carry the video streaming packets from both surveillance cameras: the camera installed in LM and the one installed in CM. For the *SingleCam_Link*, since it only has to carry video streamed by the camera installed on CM to LM, the bandwidth requirements are lower.

The Iperf tool [136] has been used to load the WiMAX network with packets and measure the maximum available bandwidth. The maximum throughput obtained for the *Aggregation_Link* and for the *Single_Cam_Link* is shown in Table 3-2.

We can see from Table 3-2 that the 7 MHz channel bandwidth for the *Aggregation_Link* provides 2.2 Mbps of throughput for the uplink channel. In this case, it is possible to carry the video from both cameras, but not with the maximum bit rate (1.5 Mbps per camera). Therefore, the best solution is to select the 14 MHz channel bandwidth, which provides 4.5 Mbps dedicated for the uplink direction, enabling the maximum video encoding rate for the video streaming.

Concerning the *SingleCam_Link*, since the distance is lower than the *Aggregation_Link*, the measured bandwidth is, as expected, higher. Only the video from one camera is streamed towards this link. Therefore, the 3.5 MHz channel bandwidth is sufficient to satisfy the Fire Prevention application bandwidth requirements (1.5 Mbps).

Table 3-2: Fire prevention WiMAX testbed propagation conditions and measured throughput

Link Direction	BW (MHz)	Distance (km)	Propagation	Uplink (Mbps)	Downlink (Mbps)	Total (Mbps)
Aggregation_Link	3.5	22.8	LOS	1.1	1.3	2.4
	7			2.2	2.7	4.9
	14			4.5	5.6	10.1
SingleCam_Link	3.5	18.8	LOS	2.0	2.4	4.4
	7			4.1	4.8	8.9
	14			7.8	9.6	17.4

3.4. Summary

It is unquestionably that WiMAX and LTE represent an important step on the evolution of 4G communication scenarios. The high throughput provided by these technologies, either in fixed or mobile environments, is a great advantage for mobile environments and the new multimedia services available nowadays.

This chapter gave an overview of the most relevant scenarios, making use of different LTE and WiMAX standards, fixed, mobile and mesh, from simple scenarios, such as using fixed WiMAX to serve as backhaul to several buildings in an urban scenario, to most complex scenarios, such as using mesh mode and relay stations balancing the traffic and serving as backhaul to mobile WiMAX. Mobile broadband scenarios based on the mobile version of WiMAX and/or on the 3GPP LTE standard were addressed, with particular attention given to seamless inter-technology handover scenarios, either driven by the imminent loss of connectivity or motivated by network resources optimization.

In terms of applications besides normal communication between users, two main types were described, namely, medical and environmental monitoring applications. The broadband and reliability characteristics of the communications using LTE and/or WiMAX access technologies makes it suitable to be used in emergency mobile situations, like on-site medical assistance, where it is required to maintain constant connectivity in usually remote locations.

With respect to the environmental monitoring application scenarios, the distant communication required by environmental monitoring is also strongly benefiting from WiMAX and LTE access technologies, as it enables simultaneously reliability, QoS, broadband and remote access. The fixed version of WiMAX is in a better position to address the static use-cases, such as remote surveillance towers for fire prevention and volcano monitoring, whereas both LTE and mobile WiMAX can be used for the mobile use-cases, such as personal and vehicle monitoring in the remote locations.

4. QoS Control for an all-IP WiMAX Network Architecture

IEEE 802.16 standard defines one of the most promising technologies for BWA, providing high performance in terms of data rate and coverage. In particular, it defines an air interface specification for fixed and mobile Metropolitan Area Networks (MANs), specifying a common MAC protocol with different physical layer specifications dependent on the used spectrum. The IEEE 802.16 MAC protocol is designed to support a wide range of communication services (data, voice and video), providing support for continuous and burst traffic, QoS mechanisms on the radio link and methods of bandwidth allocation.

One distinct feature of IEEE 802.16 is the explicit integration of QoS mechanisms over a connection-oriented transaction design. Each packet transmitted over the air interface between the Subscriber Station (SS) / Mobile Node (MN) and the Base Station (BS) is associated with an uplink or a downlink Service Flow (SF) that specifies the scheduling service and the related QoS parameters, like maximum and minimum rate, jitter and priority. Such SFs can be created, changed and deleted by using IEEE 802.16 signaling, more precisely the Dynamic Service Addition, Change and Deletion (DSA, DSC and DSD) MAC management messages. The specification defines three different SF statuses: provisioned, admitted or activated. In the first case, the SF is only provisioned via the Network Management System (NMS), but resources are not allocated. For admitted SF so-called soft-resources are reserved but data transmission is still not possible. The later is only possible with a SF in active state, which then is associated with a set of assigned resources to be used for carrying traffic data. The mapping between the incoming packets in the WiMAX system and the SFs is made by specific classifiers associated with each active SF.

The IEEE 802.16 standard, however, only addresses the air interface specification, including the QoS model between BS and SS/MN. It is the WiMAX Forum which complements IEEE 802.16 wireless specifications with the definition of the WiMAX Network Reference Model (NRM), based on an all-IP platform [137] [138]. This architecture includes a whole set of general functional entities required to deliver broadband wireless services. While the WiMAX NRM defines a set of logical components and interfaces, it does not define any specific implementation details but only motivates the application of open standards. It is left to system integrators how to build a complete architecture based on the NRM, either from scratch or based on commercial network components.

The presented architecture in this chapter, developed in the scope of the European research project WEIRD [139] [140], is designed to provide an efficient solution for a WiMAX, QoS-enabled, end-to-end all-IP platform in compliance with the WiMAX Forum guidelines. The proposed solution is compliant with the WiMAX NRM and improves existing features and introduces additional functionalities. In order to provide a complete end-to-end QoS support, the Next Step In Signaling (NSIS) [32] [34] protocol suite is integrated to reserve resources in the Radio Access Network (RAN), Access Network (AN) and Core Network (CN). NSIS was chosen due to its usability and adaptability to multi-domain and QoS contexts. From the applications perspective, the designed architecture must also address the support of multimedia applications based on the Session Initiation Protocol (SIP) [11] with specific QoS requirements. The choice to use SIP-based applications is due to the fact that this protocol is the de-facto standard in Next Generation Networks (NGNs) based on the IP Multimedia Subsystem (IMS) [10]. This approach allowed the integration of the IMS vision with the emerging IEEE 802.16 standards in order to guarantee end-to-end QoS for multimedia applications [141]. Besides SIP-based multimedia applications, legacy applications with QoS requirements are also supported.

One of the principal features of the presented architecture is the support for end-to-end QoS achieved by the integration of resource control in the WiMAX network segment and the resource management in the wired domains and in the CN. In order to address the envisaged end-to-end QoS support for WiMAX, cross-layer mechanisms are required to enable and facilitate the communication between the entities and protocols of the higher layers with the WiMAX network. Therefore, under the scope of this Thesis, a cross-layer framework that enables seamless communication between the WiMAX technology and the upper layers was proposed. In this sense, the so-called WiMAX Cross-Layer Manager (WXLM) is defined, providing a set of cross-layer services from the WiMAX link to the upper layers [142] [143]. The proposed WXLM comprises a middleware management and control layer between the WiMAX technology and the network layer, hiding the WiMAX technology specific functionalities from the network control plane.

Detailed signaling diagrams are also studied and described to thoroughly present the integration of the abovementioned functionalities – WiMAX, end-to-end QoS signaling, multimedia and legacy applications with real-time QoS constraints and cross-layer mechanisms. To finalize, the performance of the proposed solutions is also addressed in a real WiMAX environment [144] [145]. Signaling and QoS measurements are provided to validate the efficiency of the designed QoS architecture for next generation WiMAX environments [146] [147].

This chapter is organized as follows: section 4.1 provides an overview of the designed QoS architecture, including the involved modules and interfaces; section 4.2 describes the details for supporting legacy and SIP based applications on the designed QoS architecture; section 4.3 thoroughly describes the WXLM, focusing on its functionalities, as well as on its internal services and correspondent interactions; section 4.4 presents a set of message sequence charts to illustrate the WXLM operation under different scenarios; finally, section 4.5 details a set of performance results obtained for the WiMAX QoS-enabled framework, and section 4.6 summarizes the chapter.

4.1. WiMAX QoS-Enabled Architecture

The main objective of this section is to provide an overview of the designed architecture. Initially, in section 4.1.1, the architecture design guidelines are described, followed by a detailed explanation of the involved modules in section 4.1.2.

4.1.1. Architecture Design Guidelines

The core objective of the proposed architecture was to enhance the WiMAX technology through the seamless integration of WiMAX-based ANs into end-to-end QoS enabled all-IP architectures, which typically include heterogeneous domains with various network technologies. The designed approach is based on cross-layer mechanisms involving the application, control and transport planes, as well as on the development of convergence layers that enable full interaction among the different planes. This solution allows the interoperability with different underlying technologies (IEEE 802.16d/e) at the transport plane and, at the same time, the support for a large set of applications characterized by different QoS requirements and signaling capabilities that can exploit and take advantage of the QoS features assured by the WiMAX technology.

The basic policy for the architecture design was to obey the guidelines for the end-to-end architecture defined by the WiMAX Forum. On top of that, the goal was to add a set of extensions. This covers, among others, features of the end-to-end QoS control plane, namely QoS signaling, reservation and control functions. The designed architecture involves all the main entities of the WiMAX NRM, such as the MN, the Access Service Network (ASN) and the Connectivity Service Network (CSN), plus some additional components in order to support the above-mentioned extensions for QoS management and control. As recommended by NRM guidelines, open standards were used for the network design. For example, the NSIS framework was chosen for resource reservation signaling along the end-to-end multi-domain path. Therefore, a so-called Connectivity Service Controller (CSC) is placed in each NRM entity (MN, ASN and CSN) in order to coordinate and process QoS/NSIS signaling, as well as the WXLM to perform the cross-layer interactions, such as resources control, in the WiMAX segment. Another example is the placement of a set of servers and proxies in the CSN providing additional functionalities such as Authentication, Authorization and Accounting (AAA), as well as monitoring and support for SIP applications. More details on these entities are presented in the following sections of this chapter.

Figure 4-1 provides a high-level illustrative overview of the WiMAX QoS-enabled architecture, highlighting the strong interactions between the lower layers that characterize the network technologies and the higher layers of the control and application planes.

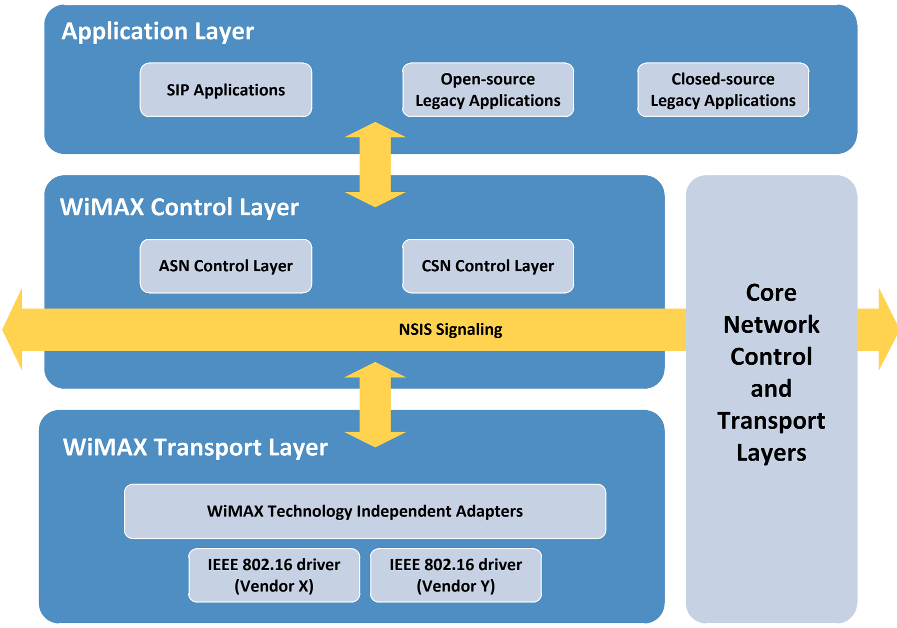

Figure 4-1: WiMAX QoS-enabled architecture overview: application, control and transport Layers

The designed system supports a wide set of applications ranging from (i) legacy applications without signaling capabilities, (ii) existing applications that can be updated in order to directly interact with the WiMAX QoS-enabled control plane and (iii) SIP applications with their application-level signaling. The complete integration between the control plane infrastructure, strictly related to the WiMAX network architecture, and the application plane allows the dynamic reconfiguration of the wireless link through the creation and modification of SFs that fit the profile of the network traffic generated by the applications. In fact, the architecture control plane is able to interact with different application signaling schemes and to translate various types of application traffic descriptions into the QoS metric used in the IEEE 802.16 domain, based on the main SF parameters (scheduling class, QoS parameters and classifiers). This flexibility allows the designed framework to adapt itself to a variety of application scenarios, characterized by specific signaling procedures.

The AAA is the component located in CSN entity and is in charge for the following functionalities:

- Check that an user or a device who is requesting services by presenting an identity and credentials is a valid user of the network services requested (authentication);
- Grants of specific types of service to an user or device, based on their authentication, what services they are requesting, and the current system state (authorization);
- Tracks the consumption of network and services resource per users for planning, billing, or other purposes (accounting).

Several levels of authentication and authorization are applied, to control access of an SS/MN and of its user(s) to connectivity services and to high-level services. Security shall therefore be applied at three different levels:

- At network level, to ensure that only authorized devices can use the WiMAX access channel. This check prevents unauthorized wireless devices to enter the network by connecting to the BS;
- At service level, to ensure that only authorized users can use network resources and then activate available services. This requires interaction with the SIP proxy and with the CSC_ASN for SIP and legacy applications authorization, respectively.
- At application level, to ensure that only authorized customers can activate applications and then use signaling for it.

The integration of the application and the control plane allows the dynamic configuration of WiMAX network resources according to the actual requirements of the active services. The resource allocation on the rest of the end-to-end path is delegated to the control plane modules located in the external networks. The interface between the WiMAX framework and the heterogeneous external domains is based on NSIS signaling, in particular on the QoS NSIS Signaling Layer Protocol (NSLP) [33]. This approach provides the required guarantees for a coherent QoS signaling along various networks exporting different transport technologies and resource control mechanisms, characterized by specific QoS metrics.

Two main issues must be considered in order to assure the same QoS level along the full end-to-end path, including the WiMAX access segment, and independently of user mobility. Firstly, the end-to-end path can include several domains, like Differentiated Services (DiffServ) [31] or Integrated Services (IntServ) [30] domains, supporting heterogeneous underlying network technologies and QoS guarantees, with different parameters and detail levels. The uniformity of the QoS level in this scenario, even with the bounds imposed by the different technologies, can be obtained using a multi-domain QoS signaling protocol like QoS NSLP and mapping the QoS description in a set of specific parameters as defined by the QoS metric supported in each domain. The QoS parameters carried in the QSPEC (QoS Specification) are opaque to the QoS NSLP, and are defined in the QoS model of the specific network technology, so that they can be interpreted only by the Resource Management Function (RMF) of the NSIS peers located in each domain.

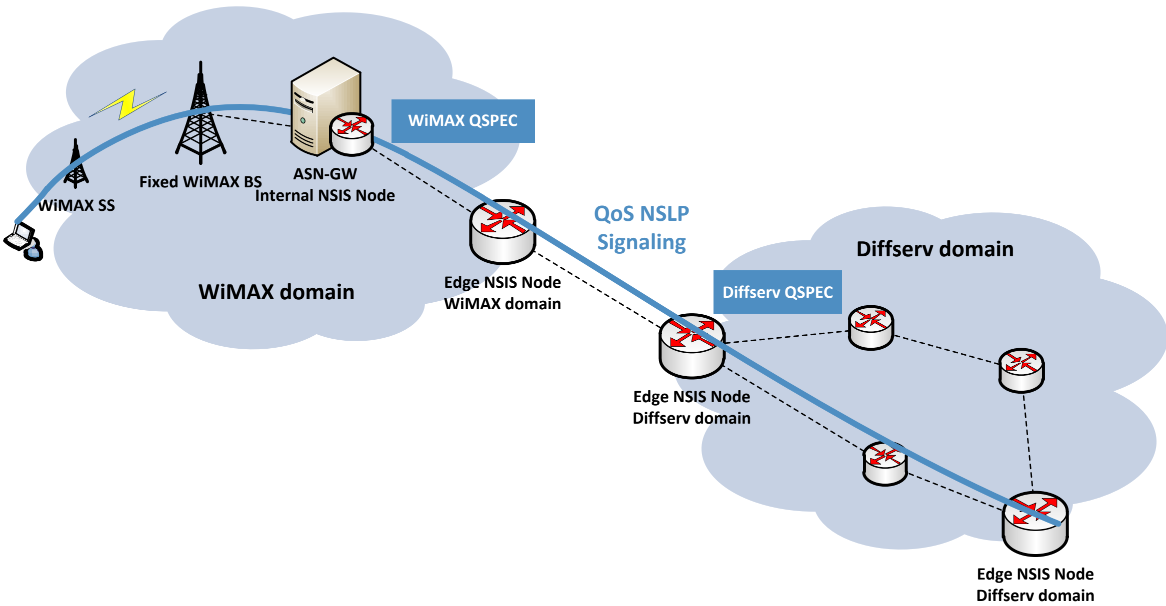

Figure 4-2: Multi-domain (DiffServ and WiMAX) QoS NSLP signaling

In case of multi-domain path, the NSIS node located at the ingress of each domain is in charge of the translation between the received QSPEC and the internal QSPEC. This QSPEC is based on the QoS parameters supported by the underlying technology of the specific domain, and it can be easily understood by the RMF of each internal NSIS node. Figure 4-2 shows an example with a scenario including a WiMAX AN and a DiffServ domain in the CN. The QSPEC carried in the QoS NSLP messages follows the DiffServ QoS model in the DiffServ domain and the WiMAX QoS model in the WiMAX domain. In particular, at the WiMAX access domain, the QoS description is based on a set of SFs characterized by the scheduling class and the WiMAX QoS parameters that are more suitable for the current session. These SFs are reserved and activated during the session setup phase using the network-initiated procedure defined as mandatory in the IEEE 802.16 d/e specifications. In this case, the SF creation is initiated by the BS and controlled by the corresponding ASN-Gateway (ASN-GW).

The architecture mechanisms provide features for both long/medium-term resource management (management plane) and short-term resource control (control plane) in the WiMAX access segments through the interaction with the WiMAX transport plane, based on a common technology-independent module and specific hardware-dependent drivers for device configuration. The full integration with the end-to-end IP architecture is assured through the seamless interaction between the WiMAX access and connectivity network and the CN, characterized by different underlying technologies. Communications between the WiMAX control plane modules, in charge of the ASN and CSN configuration, and the control plane of the external CN is based on the multi-domain NSIS signaling protocol, providing a comprehensive solution for end-to-end QoS and mobility [148].

As illustrated in Figure 4-3, two main network scenarios are supported by the architecture: the single-hop and the two-hop, also known as concatenated/backhaul scenario. The single-hop scenario is composed by the mobile version of WiMAX directly connected to the mobile subscriber, whereas the two-hop scenario is composed by the fixed version of WiMAX in the first-hop and a Wi-Fi or a Local Area Network (LAN) link on the last hop. In this case the fixed WiMAX link is used as a backhaul solution for the LAN or Wi-Fi network. An ASN may control and aggregate several BSs linked through an ASN-GW to the CSN. The ASN-GW plays here both the data gateway role, and also the control role for ASN. Connectivity with other networks may be realized via IP backbone [149] [150].

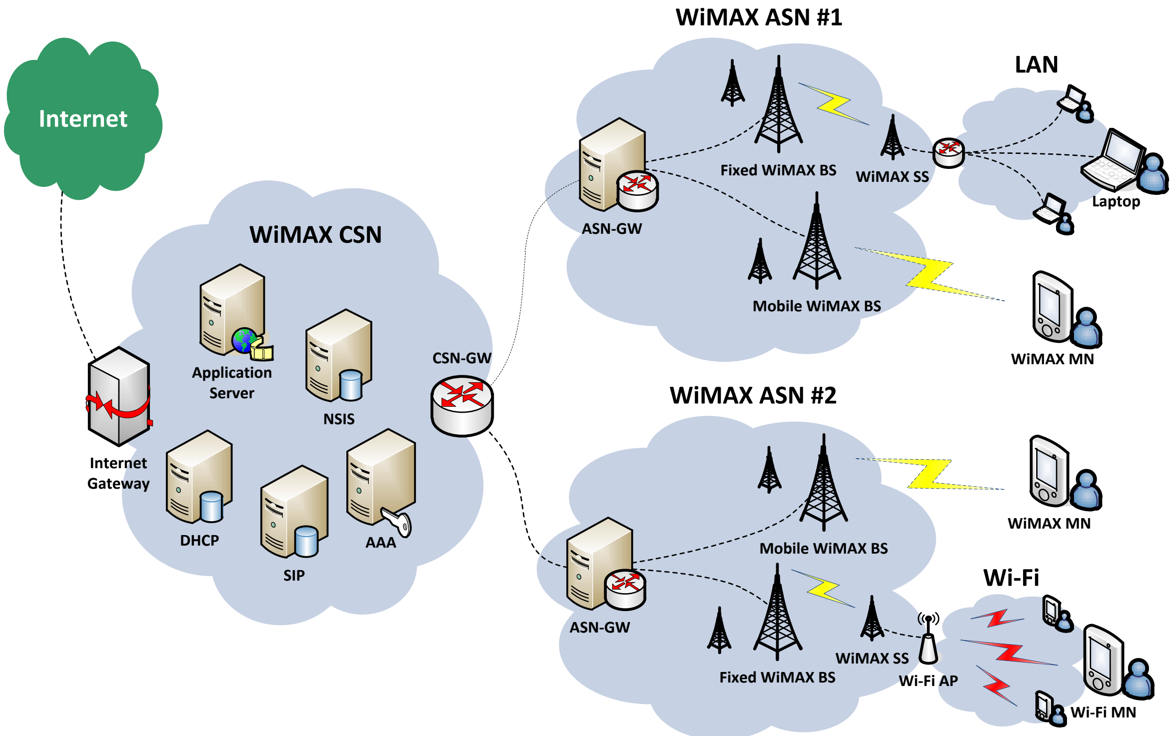

Figure 4-3: Supported WiMAX network scenarios

4.1.2. Architecture Details

At the control plane, a module called CSC manages each network segment. CSCs represent the main coordination points of the architecture and control all procedures concerning the application sessions and

QoS reservations in their related segment. The communication between the three existing instances of CSC (CSC_MN, CSC_ASN and CSC_CSN) is based on NSIS signaling. NSIS decomposes the overall signaling protocol suite into a generic (lower) layer and specific upper layers for each specific signaling application. At the lower layer, General Internet Signaling Transport (GIST) [34] offers transport services to higher layer signaling applications. Above this layer, the QoS NSLP supports any protocol within the signaling application layer.

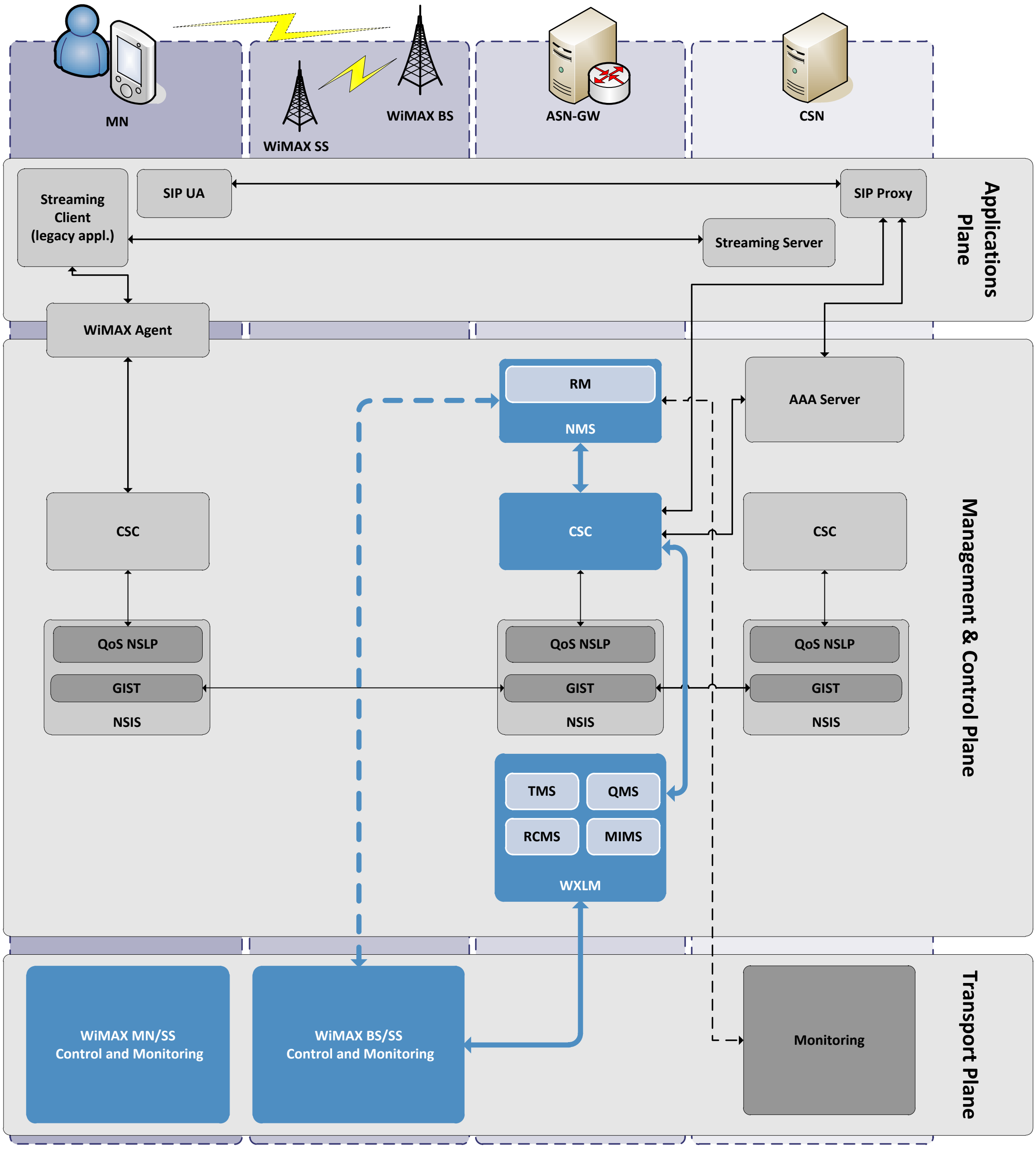

Figure 4-4: WiMAX QoS-enabled architecture

As shown in Figure 4-4, the interaction between the application plane and the control plane follows two different approaches according to the application type. For legacy applications, a specific module is specified in the MN – the WiMAX Agent (WA) – which adapts and configures the QoS parameters as required by closed-source legacy applications, allows the CSC_MN to retrieve all information about the current services, such as traffic type, required bandwidth, maximum supported latency and jitter, classifiers and authorization data. In this case, CSC_MN is the main coordinator and the initiator of the end-to-end

QoS NSIS signaling. CSC_MS translates the application traffic description into an initiator QSPEC based on the WiMAX QoS model and initiates the NSIS signaling towards the CN. The QoS NSLP messages are intercepted by each NSIS node along the end-to-end path, where the QSPEC is processed by the related RMF and the corresponding resources are allocated in the specific segment, according to the QoS attributes included in the QSPEC. In particular, CSC_ASN, located at the ASN-GW, has the role of the RMF for the WiMAX AN, while CSC_CSN acts as RMF for the connectivity service network.

On the other hand, the QoS signaling for SIP applications is based on the network-initiated approach, following the IMS model. An enhanced SIP Proxy located at the CSN intercepts the incoming SIP messages from the SIP User Agents (UAs) and interacts with the CSC_ASN. This interface is based on the Diameter Gq' [151] specification: the description of the SIP session is retrieved from the Session Description Protocol (SDP) [152] messages and all the information concerning media types, bandwidth and classifiers is mapped in a Diameter Authentication Authorization Request (AAR) message and sent to the CSC_ASN. In this case the CSC_ASN has a dual role: it is responsible for the resource allocation in the WiMAX segment and acts as NSIS initiator for the end-to-end QoS signaling through the CN, creating the initiator QSPEC.

The tight coordination between the SIP signaling at the application layer, and the resource reservation through the QoS NSIS signaling at the control plane allows the specified system to support both QoS-enabled and QoS-assured models for SIP applications. In the former case, the actual bandwidth allocation along the end-to-end path does not have an impact on the procedures for the call setup, but only on the quality of the audio/video for that call. The signaling at the application layer and at the control layer are two distinct, parallel processes: the NSIS signaling is only triggered by SIP signaling, and then they can both proceed without interfering with each other. On the other hand, in the QoS-assured model the successful resource allocation along the full path is a pre-condition for the establishment of the SIP session and the two procedures must be coordinated at the ASN.

At the ASN, resource allocation must be authorized through Diameter message exchanges between the CSC_ASN and the AAA Server located in the CSN, following the specifications of the Diameter QoS application. This procedure includes two different phases: first the user is authenticated through the user credentials conveyed by the NSIS signaling, and thereafter the resource utilization is authorized, according to the user profile and the QSPEC specifications.

All functions related with the WiMAX system are managed and controlled by the WXLM, which can be seen as the WiMAX link manager. The WXLM provides a set of WiMAX cross-layer services to the upper layers, such as QoS, mobility, MN status and authentication. The WXLM functionalities and internal services will be thoroughly explained in section 4.3. In brief, in what concerns QoS, the WXLM is responsible for the SFs and Convergence Sublayers (CS) control (including Ethernet, IPv4 and IPv6 classification), as well as for admission control tasks on the WiMAX link. Furthermore, the WXLM acts as an abstraction layer between the upper parts of the architecture and the lower level modules. It hides all WiMAX technology related functionalities from the upper layers, keeping them independent and oblivious of WiMAX-specific QoS characteristics. The WiMAX SF creation can be performed following the provisioned or the dynamic model, either using the one-phase or the two-phase activation procedure, as defined by the IEEE 802.16 specifications. Each SF is firstly created with the provisioned status allowing efficient resource utilization. When required by new user service sessions, the related SFs can be immediately activated (one-phase model) or first admitted and then activated (two-phase model). The system architecture adopts the latter model for SIP applications: during the procedure for the session setup the SFs are only admitted, and subsequently activated in order to carry the media traffic [142] [143] [153].

Moreover, the WXLM is also responsible for communicating with the WiMAX BS. It abstracts the specific details of each WiMAX equipment vendor from the rest of the architecture through a single module, called Generic Adapter (GA), that handles the common interface with the remaining services of the WXLM, and one or more Vendor Specific Adapters (VSAs) to control each specific WiMAX system (see section 4.3.5). This solution provides the flexibility required to support a large variety of WiMAX equipment vendors, without any significant impact on the higher layers. New WiMAX equipments can be added to the system through the development of a single hardware-dependent driver supporting a subset of the Application Programming Interface (API) exported by the GA. With this approach, different WiMAX equipments can be integrated into the architecture by developing a VSA for each new vendor equipment. From all modules defined on the architecture, VSAs are the only dependent on the specific WiMAX equipment used.

Hereafter, summarizing the above description, the architecture modules installed on each one of the WiMAX NRM entities are briefly described. With respect to the CSN, the following modules are defined:

- *SIP Proxy*: handles SIP signaling, intercepts and processes SDP messages and interacts with the CSC_ASN to request resource reservation for SIP applications;
- *Authentication, Authorization, and Accounting (AAA) server*: provides functionalities for user authentication and QoS authorization, interacting with the SIP Proxy and the CSC_ASN;
- *Connectivity Service Controller (CSC_CSN)*: manages resources in the CSN, performing admission control in the CSN and coordinating requests coming from the related NSIS module;
- *NSIS controller (NSIS_CSN)*: located on the border of the WiMAX domain, acts as an edge QoS NSIS Entity (QNE). It is in charge of the translation between the parameters of the WiMAX QoS model adopted in the ASN and the specific QoS model adopted in the external domain.

Regarding the ASN-GW, it includes the following modules:

- *Network Management System (NMS)*: contains functionalities for monitoring and network configuration. It includes the Resource Manager (RM) module, used to request the static resources provisioning in the WiMAX segment;
- *Connectivity Service Controller (CSC_ASN)*: main coordination point for QoS management, resource allocation, ASN admission control and QoS authorization. It receives requests from the RM for resource pre-provisioning, and from SIP proxy and NSIS module for dynamic resource allocation. The CSC_ASN includes also a database to store information on WiMAX network topology, SF pre-provisioning and active service sessions, with a description of resource utilization. Such information can be used to perform admission control in the ASN or to provide monitoring functionalities;
- *NSIS controller (NSIS_ASN)*: manages NSIS signaling acting as a generic QNE or a QoS NSIS Initiation (QNI). In the former case, it processes requests coming from the NSIS peer and interacts with the CSC_ASN that assumes the role of RMF. In the latter case, it is triggered by the CSC_ASN to initiate a new resource reservation;
- *WiMAX Cross Layer Manager (WXLM)*: provides a set of cross-layer services between the WiMAX system and the network layer, such as QoS management, mobility management, network topology discovery and WiMAX equipment vendor independency. It performs admission control on the WiMAX segment and manages all the resources in the WiMAX RAN. It receives requests from the CSC_ASN and handles the creation, modification and deletion of SFs. Furthermore the WXLM deals with the specificities of each WiMAX equipment vendor by translating generic requests into WiMAX vendor-specific messages. Further details about the WXLM and its internal modules will be provided in section 4.3.

Finally, the main modules included in the MN are the following:

- *WiMAX Agent (WA)*: provides support for closed-source, non-customizable legacy applications to request resource reservation specifying QoS parameters and classifiers; implements the WiMAX Legacy Applications Interface (WLAI) with the CSC_MN;
- *Connectivity Service Controller (CSC_MN)*: handles requests coming from the WA or from signaling applications, performs admission control in the MN segment and sends requests to the NSIS module to initiate the end-to-end QoS signaling;
- *NSIS controller (NSIS_MN)*: manages the NSIS signaling and supports the QoS NSLP. It acts as a QNI, the first node in the sequence of the QNEs that issue a reservation request for a session.

Summarizing, the architecture integrates the following QoS support functionalities:

- Static WiMAX resource pre-provisioning: wireless resources are statically configured between the BSs and the MNs under control of the ASN. SFs with different scheduling classes are created to support traffic flows with different QoS requirements. In this phase, SFs are only provisioned and they cannot be used to transfer data;
- Dynamic resource allocation for legacy applications: the WLAI signals QoS requirements for new services and requests resource reservation to the CSC_MN. The NSIS module located on the MN initiates the end-to-end NSIS signaling towards the receiver. Signaling is intercepted at the ASN-

GW and, if the request is authorized and resources are available, suitable SFs in the WiMAX segment are activated;
- Dynamic resource allocation for SIP applications: SIP signaling coming from the SIP UA located on the MN is intercepted and processed by the SIP Proxy of the CSN. The SIP Proxy extracts QoS parameters from SDP messages and interacts with the CSC_ASN that coordinates the activation of the WiMAX SFs adopting the IEEE 802.16 two-phase activation model;
- QoS authorization: each request for dynamic resource allocation must be authorized according to the user service profile, through a message exchange between the CSC_ASN and the AAA server;
- Admission control: each CSC and the WXLM includes an admission control module to allow control of resource reservation and allocation on the respective segment. The admission control is based on the current traffic load and the network performance;
- Monitoring functions: provided to get information about the WiMAX network topology, the wireless resource utilization and the active application sessions.

The presented architecture was developed within the framework of the European IST collaborative project WEIRD [139] [153] [154] [155]. The architecture modules and interfaces designed and developed under the scope of this Thesis are highlighted in *blue* in Figure 4-4, more precisely, the WXLM, as well as the attendants and interfaces for the CSC_ASN and the NMS.

In the next section, a detailed description about the WiMAX QoS-enabled signaling procedures for both legacy and SIP applications is provided.

4.2. QoS Signaling and WiMAX Resource Allocation

As discussed earlier, the twofold interaction between the control plane and the application plane, on the one hand, and between the control plane and the transport plane, on the other, is of great importance: the former allows the acquisition of the application QoS requirements for the resource control during the session setup and tear-down phases, while the latter enables the control plane to modify the resource allocation on the underlying transport technologies, in this case WiMAX.

During the session setup phases, the CSCs interact with the service layer in order to retrieve information from the applications, regarding the traffic type and the required QoS parameters. In particular, two different approaches can be adopted in order to support both legacy and IMS like applications, based on SIP and SDP signaling.

The following sub-sections address the QoS management procedures in the designed architecture to support resources provisioning (section 4.2.1), legacy applications (section 4.2.2) and SIP applications (section 4.2.3) [156].

4.2.1. Resources Provisioning

The WiMAX QoS-enabled architecture should be flexible enough to allow efficient resources management and control. The general idea is that medium-long term resources allocation, also known as resources provisioning, can be done by the management plane, thus preparing in advance the resources to be used in the future by the high level services (e.g. web, email, …). From the granularity point of view, the provisioning can be done at:

- Individual or aggregated level (not per individual flow) in the MN/SS – BS zone of the chain;
- Aggregated level in the zones BS – ASN-GW, ASN-GW – CSN and inside or between CSNs.

Figure 4-5 sketches the different segments of the WiMAX network. The picture also shows which links are subject of resource provisioning, and on which level this provisioning is performed. Irrespective of the link technology between two entities, in order to support QoS, the total capacity has to be determined in advance and possibly divided among the supported traffic classes, i.e. supported services. In the presented architecture, the logical module in charge of this task is the RM. This module is a composite of several functions and has a set of interfaces, where the most important ones are an Admin Management Interface (AMI) and the interface with the CSC_ASN. The AMI provides direct access to the RM, while the CSC_ASN interface is used for signaling in order to receive resource management orders and to communicate with the WXLM.

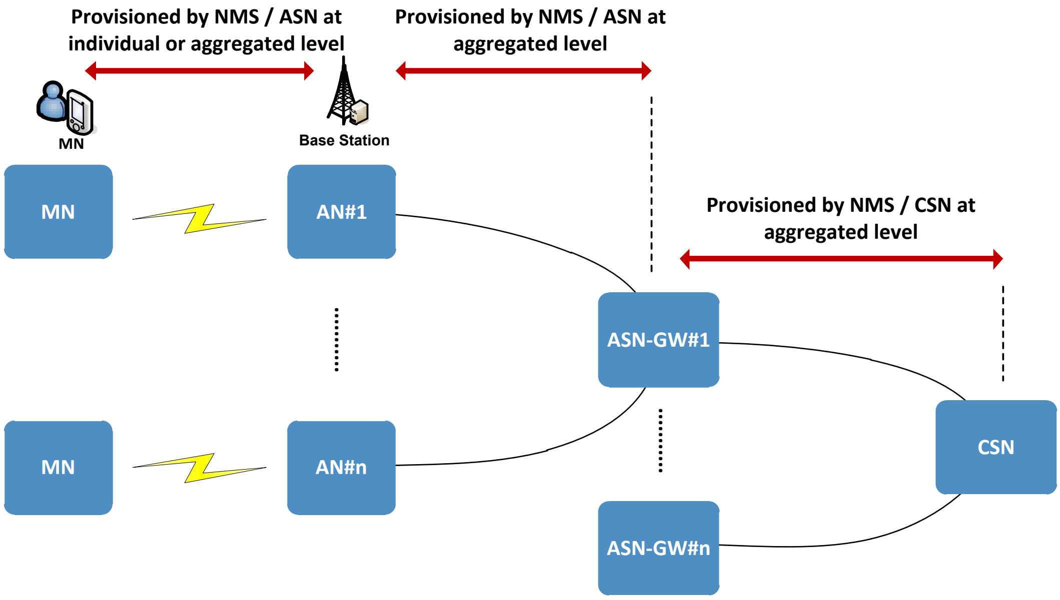

Figure 4-5: WiMAX resources provisioning [27]

Resources provisioning can be static or dynamic. In the static case, a certain amount of resources required for a class/service is allocated and immediately enabled given that the requestor successfully passes the authentication and authorization procedure, triggered by the RM after receiving a resource request. This AAA request is communicated back to the CSC_ASN, which in turn forwards the request to the AAA module. Once access is granted, available resources are estimated by the admission control module by the CSC_ASN for the ASN segment and by the WXLM for the WiMAX segment, and if available, immediately enabled. As the name implies, once enabled, no further changes are possible, except a complete release. This is usually the method for long-term resources provisioning, where the amount of resources is determined by traffic matrix estimation and future prediction. Typically, the inputs for this dimensioning task are commitments contracted between a Network Service Provider (NSP) and its customers, documented in Service Level Agreements (SLA), which cover business relations, and their Service Level Specifications (SLS), which define the technical part.

In contrast to the former feature, dynamic resources provisioning is also supported. The major difference compared to the static case is that resources can be requested and admitted, but do not necessarily have to be enabled immediately; instead, they can be enabled by a subsequent request. Naturally, the reason for featuring this by the architecture is to support per-flow QoS on the WiMAX link. As mentioned before, this can be accomplished via the AMI, but the common method anticipated by the architecture is to deploy the inherent NSIS QoS signaling facility or even SIP signaling, as described in the later sections. These requests are handled by the CSC_ASN, translated in resource provisioning requests and communicated to the WXLM.

4.2.2. QoS Management for Legacy Applications

The specified architecture is not limited to applications with native SIP or NSIS modules, but aims at supporting a large number of different applications. Such applications can be categorized into two distinct groups: applications that allow customization, i.e. open source software, and their counterpart, i.e. closed source software. To support the first type of applications, the WLAI was defined, providing an interface to the NSIS framework. The WLAI provides a set of functions among which QoS signaling is one example. In brief, the WLAI provides an interface to the complete NSIS framework. To enhance customizable applications with QoS features given this interface is rather straightforward.

In order to support closed-source applications, the WA has been developed. This software module basically serves as a translator. It is an off-line pre-provisioning module that configures the WiMAX channel before the application is launched. This module is pre-configured with application specific QoS requirements and triggers the resource allocation interaction with the CSC_MN through the WLAI. The QoS request is processed by the CSC_MN, which triggers the NSIS module to initiate end-to-end resource reservation. In this scenario, the CSC_MN acts as a QNI and is the main entity that handles and coordinates QoS signaling. Since SF management obeys a network-initiated approach, the MN QNI is not actively involved in WiMAX resource allocation, but only handles end-to-end signaling. In particular, the QNI creates the NSIS messages for the allocation, modification and release of resources required by the application sessions through the creation of *Reserve*, *Update* and *Tear-Down* QoS NSLP messages.

As illustrated in Figure 4-6, individual application's QoS parameters and classifiers are encapsulated in the QSPEC object while user credentials are part of the *AUTH_SESSION* object. These values are extracted at the ASN-GW and processed by the CSC_ASN, which subsequently performs QoS authorization and admission control (in cooperation with the WXLM), and in case of success allocates resources in the WiMAX segment. The CSC_ASN is the RMF in charge of ASN configuration for both the wireless and the wired link (between the BS and the ASN-GW).

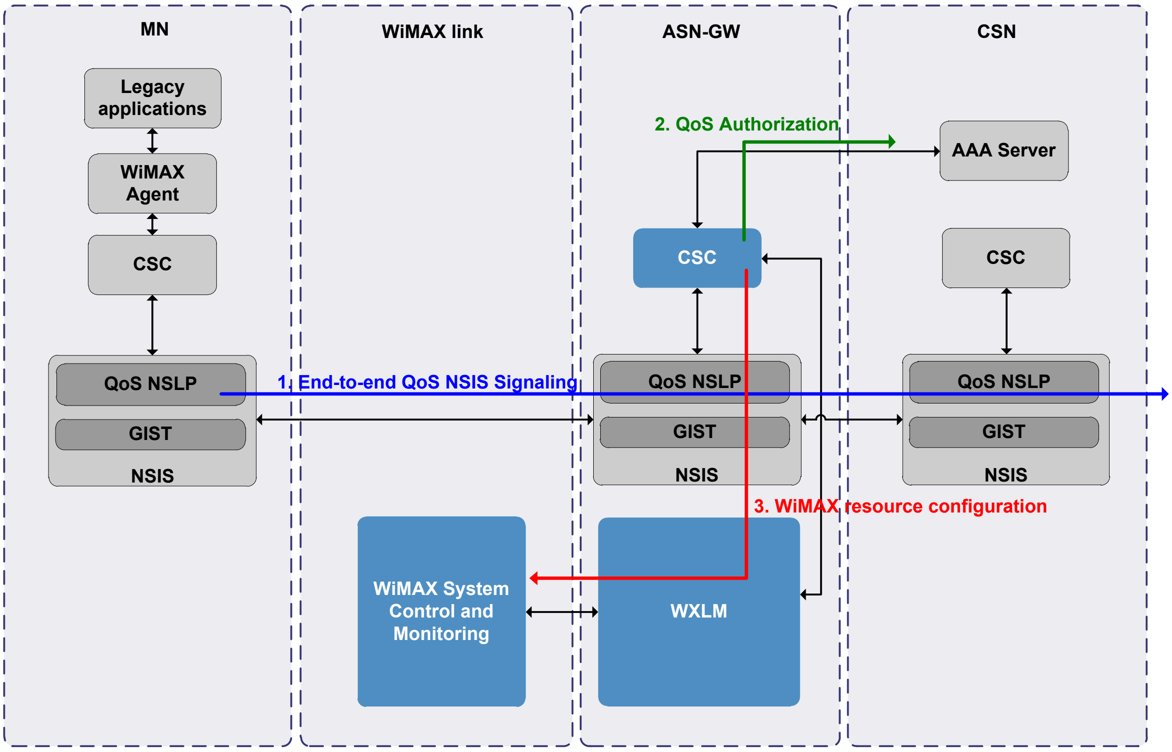

Figure 4-6: Host-initiated QoS signaling and resource reservation

In case of successful resource reservation the QoS signaling messages are forwarded and processed along the path. The NSIS messages are similarly processed by all nodes located in the CSN and the CN.

It should be noted that while both, the NSIS nodes on the SS/MN and on the ASN-GW are part of the WiMAX domain, other NSIS nodes towards the destination may be part of different QoS domains, like DiffServ or Intserv clouds. The resource configuration in each segment is therefore based on the respective QoS model. Interoperability between different QoS models is a well-known issue and assured by mechanisms defined by the NSIS protocol suit. Commonly, a mapping between the different types of QSPEC objects, one for each QoS model, is performed by domain edge nodes. For example, the initiator QSPEC created by the SS/MN QNI reflects the WiMAX QoS model and includes all the QoS parameters required for the configuration of WiMAX SFs. Beyond the WiMAX segment, the initiator QSPEC must be mapped to local QSPECs and be placed on the top of the QSPEC stack such that internal nodes process only the local QoS parameters, omitting the attributes that otherwise could not be understood anyways.

4.2.3. QoS Management for SIP Applications

For native IMS/SIP applications, the architectural approach is based on the integration between pure SIP signaling and mechanisms to allocate resources in the WiMAX network, as well as to request resource reservation towards the CSN. The WiMAX resource allocation includes the creation and the activation of the SFs for each media flow (audio and/or video) of the SIP call, and is handled using a network-initiated approach, where the ASN-GW is the entity in charge of the BS configuration for the SF management. The two-phase activation model, as defined in the 802.16 standard, is adopted to activate WiMAX SFs in order to get an efficient bandwidth utilization: during the call establishment, each SF is admitted without any actual usage, and it is activated only when the capability negotiation is concluded.

The resource allocation for a SIP call, involving two endpoints located in the same ASN, requires the creation of uplink and downlink SFs for each media component. In this scenario, no resources are allocated in the CSN. On the other hand, the resource reservation in the CSN is required if the SIP clients are located in different ASNs. In this case, each SIP client is registered in a specific SIP Proxy located on the CSN. In order to obtain a consistent level of end-to-end QoS along the end-to-end path, resources must be made available not only in the two ANs, but also along the path between the two ASN-GWs. Therefore, the required QoS signaling interaction is based on the NSIS protocol, in order to support the interoperability among various QoS-enabled domains, characterized by different QoS metrics.

The overall approach for SIP applications is based on the following assumptions:

- SIP signaling is initiated by a standard SIP UA on a host connected to the BS, and is intercepted and processed by the Application Function (AF) of the SIP Proxy located in the CSN;
- SDP protocol is adopted to describe multimedia sessions;
- Codec negotiation during session setup can be supported. One participant offers the other a description of the desired session, and the other participant answers with the desired session from its perspective;
- A QoS assured model is adopted. The call can be established only if the requested/required QoS specified in SDP messages as attributes of the media can be provided;
- Each SIP method must be authorized through a Diameter message exchange between the SIP Proxy and the related AAA server. Similarly, each WiMAX resource utilization must be authorized according to the QoS level required for the SIP call and the caller user profile. This QoS authorization is performed through a Diameter message exchange between the ASN-GW and the AAA server.

The signaling process can be considered as a two-phase process. In the first phase, the calling proxy extracts the maximum bandwidth from the SDP payload and requests resource reservation for the worst-case (maximum bandwidth) to the related CSC_ASN. In this phase, resources in the WiMAX network are only admitted and cannot be used to carry traffic data. In the second phase, both proxies modify or confirm bandwidth requirements after the codec negotiation phase is concluded and WiMAX SFs are activated.

The interface between the SIP Proxy and the CSC_ASN is based on the Diameter Gq' interface. Two types of Diameter messages are supported: the *Authorize Authenticate Request/Answer (AAR/AAA)* to request the resource reservation, and the *Session Termination Request/ Answer (STR/STA)* to signal the termination of the service session.

The interface between the SIP Proxy and the AAA server is based on the ETSI/TISPAN Cx/Dx interface, and involves the *Multimedia Auth Request/Answer (MAR/MAA)* Diameter messages for the authentication and the user authorization. Each SIP method is authenticated using the HTTP Digest Authentication [157].

The interface between the ASN-GW and the AAA server is based on the Diameter QoS Application [158]. The QoS authorization is performed through the exchange of *QoS Authorization Request/Answer (QAR/QAA)* messages that include specific Attribute Value Pairs (AVP) for the description of the required QoS.

Figure 4-7 shows the QoS signaling procedures for IMS-like applications. The QoS signaling follows the network-initiated approach and it is strictly connected to the application layer SIP/SDP signaling. The SIP Proxy located at the CSN intercepts the SIP signaling between the SIP UAs, extracts the session description from the SDP messages, and performs user authentication and authorization with the AAA. The QoS parameters are forwarded to the CSC located at the ASN (CSC_ASN), through a set of Diameter messages describing the media flows included in the sessions, where they are translated into WiMAX parameters. In this case, the QoS NSIS signaling follows the edge-to-edge model, since it is initiated and controlled by the CSC_ASN.

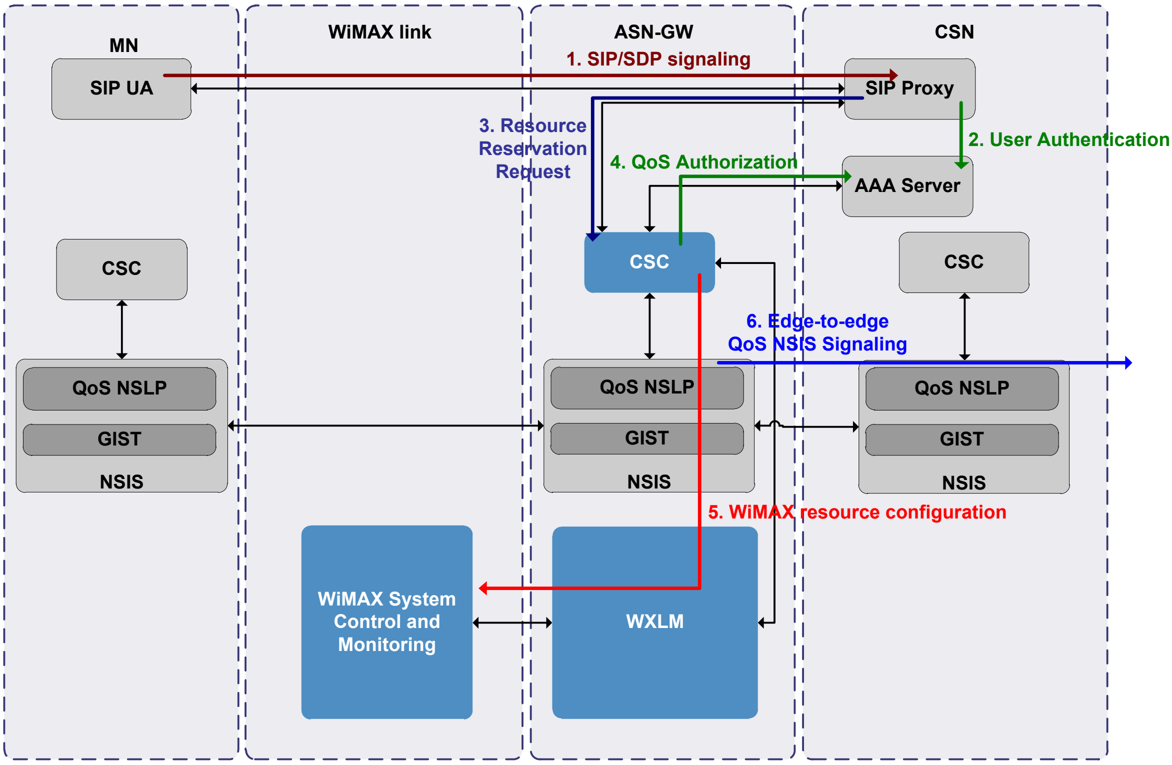

Figure 4-7: QoS signaling and resource reservation for IMS-like applications

For both legacy and IMS-like applications, WiMAX resource reservations are handled by the ASN-GW through the interaction of the CSC with the lower planes. In particular, at the link layer level, the WXLM module manages all the WiMAX technology related functionalities, like SF creation, modification and deletion, enforcing the QoS decisions on the WiMAX system through a set of technology dependent adapters.

The next section exhaustively addresses the WXLM internal services and functionalities.

4.3. WiMAX Cross-Layer Manager System

An important aspect of next generation networks is the seamless integration of heterogeneous network technologies. Future network architectures will provide seamless QoS support, mobility and security, among other features, which are crucial for the success of these networks. Taking into account the convergence scenario envisioned in the telecommunications area, it is essential that different access technologies, wired and wireless, are able to work together, allowing mobile users to handover between them seamlessly. In this sense, in order to integrate WiMAX technology in next generation environments, one needs to support a cross-layer framework that enables seamless communication between WiMAX and other access technologies, as well as with the QoS, security and mobility management protocols.

Nowadays, standardized mechanisms for both network layer and link layer are already in place. For example, on the network layer side, QoS signaling protocols and frameworks, such as NSIS and DiffServ respectively, as well mobility management protocols, such as basic Mobile IP (MIP), version 4 [35] and version 6 [36], Fast MIP (FMIP) [37] and Proxy MIP (PMIP) [38] are well established. However, one of the major gaps is the inter-layer connectivity, also known as cross-layer, between the network and the link layer functions. One particular example is the WiMAX access technology, which requires an efficient communication with the network layer to exploit all its functionalities. To establish an efficient communication between the network and the WiMAX system lower layers, the WXLM system is proposed.

The following sub-sections (4.3.1, 4.3.2, 4.3.3, 4.3.4, 4.3.5) address the cross-layer management services delivered by the WXLM to the upper layers.

4.3.1. WXLM Management Services

The WXLM is responsible to provide all the required cross-layer services between the WiMAX system and the network layers, such as QoS, mobility, AAA, security, network topology, radio resources management, terminal management, multicast and broadcast. The WXLM system, illustrated in Figure 4-8, comprises a middleware layer between the WiMAX technology and the network layer, hiding the WiMAX technology specific functionalities from the network control plane.

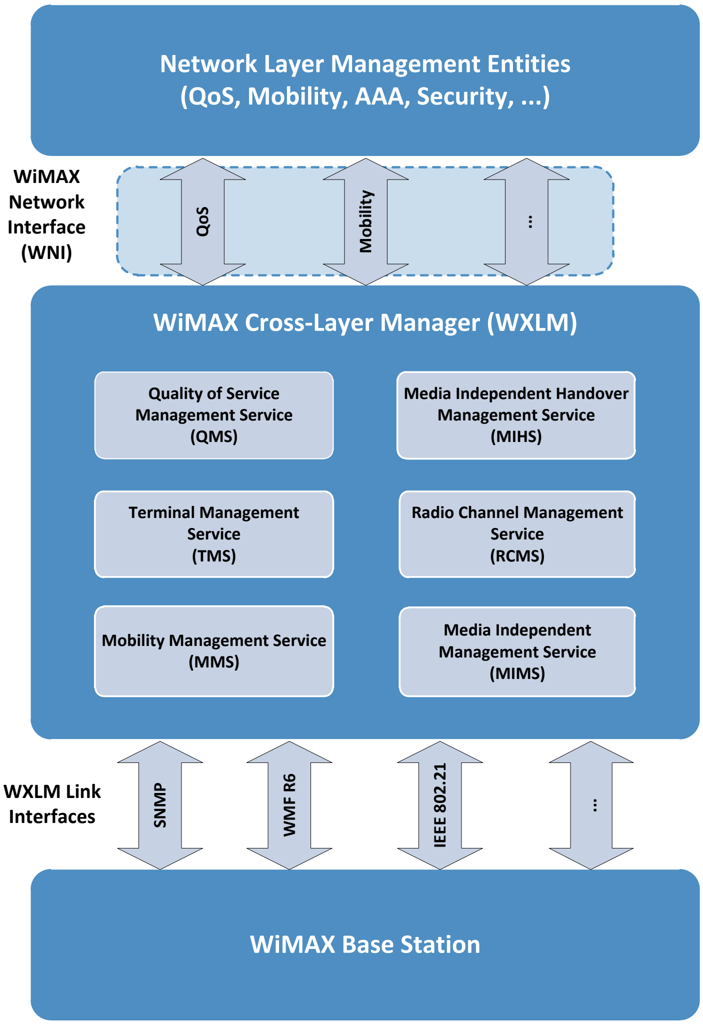

Figure 4-8: WiMAX Cross Layer Manager (WXLM) services

To interact with the network layer, the WXLM provides a dedicated interface, known as WXLM Network Manager (WNI), comprising, among others, support for the abovementioned services. Likewise, the WXLM Link Interfaces (WLI) also encompass several ways to interact with the link layer technologies. The preferred and most appropriated interface between the WXLM and the WiMAX BS is established using the standardized WiMAX Forum R6 reference point [137]. Nevertheless, we cannot assume beforehand that all WiMAX systems support the WiMAX Forum R6 standardized interface. For example, current commercial WiMAX equipments available on the market, though already certified by the WiMAX Forum, only support Simple Network Management Protocol (SNMP) [40], Hypertext Transfer Protocol (HTTP) [159] or Telnet

Protocol [160] to manage the WiMAX equipments. Hence, the WXLM system must be flexible to support any type of interface with the link layer as alternatives to the preferred WiMAX Forum R6 interface.

The functionalities provided by the WXLM are grouped on different management services. As illustrated in Figure 4-8 and briefly summarized in Table 4-1, the following set of management services are provided by the WXLM: Terminal, Radio Channel, QoS, Mobility, Media Independent Handover (MIH) and Media Independent.

Table 4-1: WXLM management services

WXLM Management Service	Description
Terminal (TMS)	Management of the terminal states (normal, sleep and idle modes), status (on, off) and network entry and exit procedures
Radio Channel (RCMS)	Management of the WiMAX radio channel information (available radio resources, SS/MN physical measurements)
Quality of Service (QMS)	QoS (Service Flows) management in the WiMAX link – including admission control procedures
Mobility (MMS)	Control of the handover context transfer between the serving and the target WiMAX links
MIH (MIHS)	Translation of the 802.21 Media Independent Handover (MIH) primitives to the WiMAX system
Media Independent (MIMS)	Manage WiMAX equipments interfaces from different vendors

Hereafter, the Terminal Management Service (TMS), the QoS Management Service (QMS), the Radio Channel Management Service (RCMS) and the Media Independent Management Service (MIMS) from the WXLM system are described in sections 4.3.2, 4.3.3, 4.3.4 and 4.3.5, respectively.

4.3.2. WXLM Terminal Management Service

A very important aspect for the network control entities is to have information about the terminals entry and exit from the WiMAX network. This applies to both fixed nodes from IEEE 802.16d – SSs, and to MNs from the mobile version (IEEE 802.16e) of WiMAX. The WiMAX network topology acquisition is important for network management operations, as well as for admission control purposes.

Briefly, the following set of procedures is required for a WiMAX terminal to access the network:

- Establish synchronization with the BS: WiMAX has an initialization procedure to eliminate the need for manual configuration. The SS/MN stores the last channel used and tries to re-acquire this downlink channel. If this process fails, the SS/MN has to scan the possible channels of the downlink frequency band of operation;
- Obtain downlink and uplink parameters: the SS/MN has to maintain synchronization and obtain the downlink and uplink parameters. For the SS/MN to be synchronized, a *Downlink Map (DL-MAP)* message must be periodically received. If the reception of a DL-MAP message fails, the SS/MN looses synchronization with the BS. After synchronization is achieved, the SS/MN must periodically receive a *Downlink Channel Descriptor (DCD)* message to maintain synchronization and obtain the transmission parameters of the downlink channel – modulation and coding schemes. A similar procedure is used by the SS/MN to obtain the uplink transmission parameters through the *Uplink Channel Descriptor (UCD)* message. After this process is completed, the SS/MN will receive a *Uplink Map (UL-MAP)* message in each frame, which is responsible for the uplink bandwidth allocation;
- Perform ranging: the SS/MN processes the *UL-MAP* message and tries to find an Initial Ranging Information Element (IE) to transmit the *Ranging Request (RNG-REQ)* MAC management message to the BS. After the BS receives the *RNG-REQ* message, it calculates the timing advance value that the SS/MN must use in uplink direction, and sends this information to the SS/MN in the *Ranging-*

Response (RNG-RSP) management message. The BS also sends power control information, as well as the Connection Identifier (CID) for the basic management connection and the primary management connection;

- Negotiate basic capabilities: when the ranging process is completed, the SS/MN sends an *SS Basic Capability Request (SBC-REQ)* message to the BS with the supported capabilities (physical parameters). The BS receives the message and sends an *SS Basic Capability Response (SBC-RSP)* management message to the SS/MN with the intersection of the SSs/MNs capabilities and the BS capabilities;
- Perform Registration: the SS/MN sends a *Registration Request (REG-REQ)* message to the BS. The BS responds with a *Registration Response (REG-RSP)* message, which has the secondary management CID included. As a consequence, the SS becomes manageable;
- Establish IP connectivity: the SS/MN will try to acquire an IP address. To configure an IP address, the Dynamic Host Configuration Protocol (DHCP) protocol is used through the usage of the secondary management CID;
- Establish Provisioned connections: finally, the BS must send *Dynamic Service Allocation (DSA-REQ)* messages to the SS/MN to setup connections for provisioned SFs belonging to the SS/MN. As a response, a *DSA-RSP* message is sent by the SS/MN to the BS terminating the SF allocation.

The above described entry procedure for WiMAX terminals is briefly illustrated in Figure 4-9.

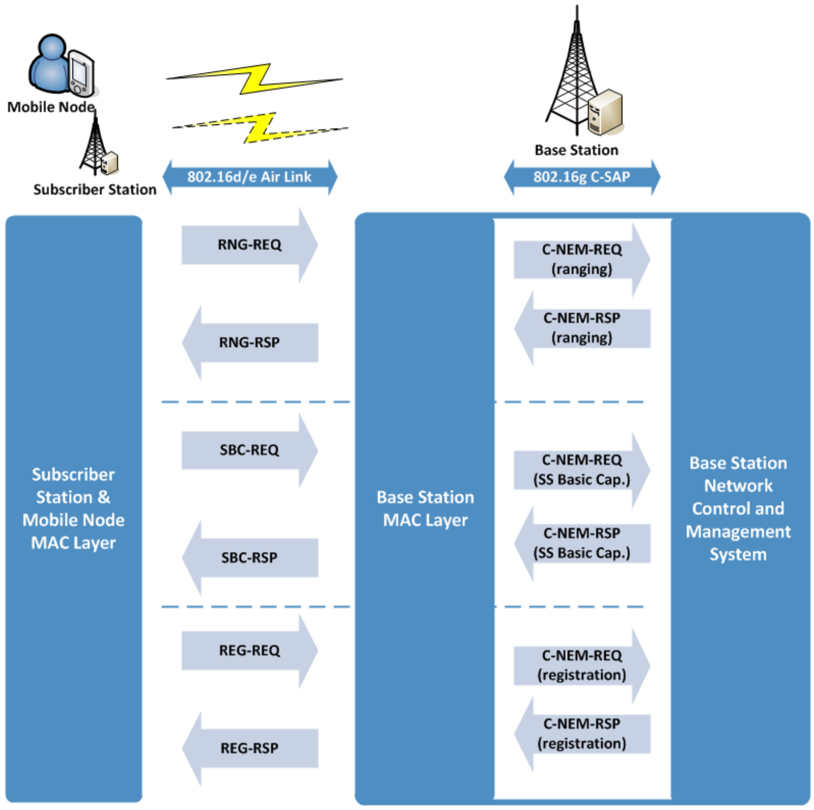

Figure 4-9: Network entry procedures in IEEE 802.16 (d/e/g)

The TMS is responsible to manage all the procedures related with the WiMAX network topology acquisition, as well as the WiMAX terminals operation status, either fixed or mobile.

Internally, as illustrated in Figure 4-10, the TMS is composed by the Network Topology Manager (NTM) and by the Terminal Status Manager (TSM) modules.

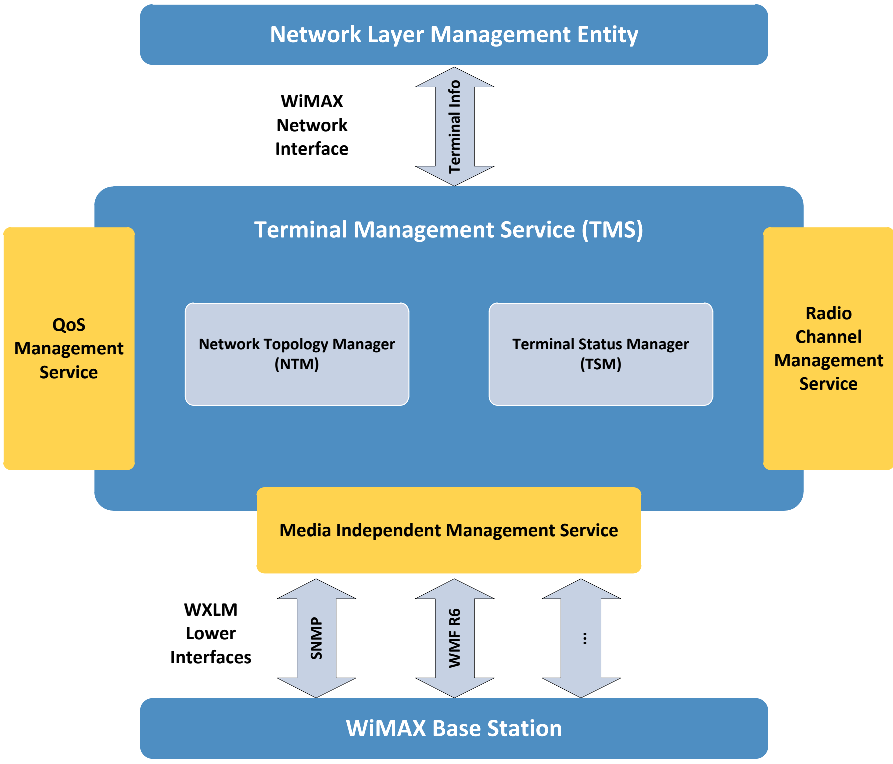

Figure 4-10: WXLM Terminal Management Service (TMS) framework

The NTM module controls the network entry and exit procedures of WiMAX BS or SSs/MNs and updates the network topology information accordingly. The information collected by the TMS during the WiMAX terminal bootstrap phase is very important to enable its access to the network services provided by the operator. In brief, information about a new MN attachment is provided by the AAA, which enables the WXLM TMS to establish the necessary signaling SFs on the WiMAX system for the network entry phase. A dedicated message sequence chart for this scenario is described in section 4.4.

The TSM controls all the procedures related with the terminal operation mode. More specifically, it is able to power up and down the WiMAX terminals, as well as to manage the sleep, idle and normal operation modes of the terminals.

The collected information about the WiMAX terminals is stored in the TMS internal repositories.

The TMS contains important information about the WiMAX network topology. It interfaces directly with the RCMS and with the QMS to provide, when required, the WiMAX BSs and SSs/MNs topology. The interaction with the MIMS is required to interface with the WiMAX equipments.

4.3.2.1. TMS Primitives

Herein the TMS primitives defined for the WNI are described.

- ***WXLM_New_BS (.indication)***

This primitive is sent by the ASN connectivity service controller to the WXLM to inform the later that a new WiMAX BS is connected. This primitive must be sent to the WXLM immediately after a new BS is connected, enabling the TMS to have an updated topology of the WiMAX network.

The *WXLM_New_BS* primitive parameters are identified in Table 4-2.

Table 4-2: *WXLM_New_BS (.indication)* – TMS primitive

WXLM Primitive	Description		
WXLM_New_BS	*.indication*	*primitive_id*	Unique ID for each primitive
		bs_mac_addr	BS MAC Address
		sector_id	ID for the sector
		sector_avail_dl_bw	Total available downlink bandwidth for the sector
		sector_avail_ul_bw	Total available uplink bandwidth for the sector

- ***WXLM_New_MN (.indication)***

This primitive is sent by the ASN connectivity service controller to the WXLM to inform the later that a new WiMAX SS/MN is connected. This primitive must be sent to the WXLM immediately after a new SS/MN is connected, enabling the TMS to have an updated topology of the WiMAX network and trigger the QMS to establish the signaling-dedicated service flows on the WiMAX link.

The *WXLM_New_MN* primitive parameters are identified in Table 4-3.

Table 4-3: *WXLM_New_MN (.indication)* – TMS primitive

WXLM Primitive	Description		
WXLM_New_MN	*.indication*	*primitive_id*	Unique ID for each primitive
		ss_mac_addr	SS/MN MAC Address
		assoc_bs_mac_addr	Associated BS MAC Address
		ss_avail_dl_bw	Total available downlink bandwidth for the SS/MN
		ss_avail_ul_bw	Total available uplink bandwidth for the SS/MN

- ***WXLM_Remove_BS (.indication)***

This primitive is sent by the ASN connectivity service controller to the WXLM to inform the later that a WiMAX BS has disconnected.

The *WXLM_Remove_BS* primitive parameters are identified in Table 4-4.

Table 4-4: *WXLM_Remove_BS (.indication)* – TMS primitive

WXLM Primitive	Description		
WXLM_Remove_BS	*.indication*	*primitive_id*	Unique ID for each primitive
		bs_mac_addr	BS MAC Address

- ***WXLM_Remove_MN (.indication)***

This primitive is sent by the WXLM to the ASN connectivity service controller to inform the later that a WiMAX SS/MN has disconnected.

The *WXLM_Remove_MN* primitive parameters are identified in Table 4-5.

Table 4-5: *WXLM_Remove_MN (.indication)* – TMS primitive

WXLM Primitive	Description		
WXLM_Remove_MN	*.indication*	*primitive_id*	Unique ID for each primitive
		ss_mac_addr	SS/MN MAC Address
		assoc_bs_mac_addr	Associated BS MAC Address

- ***WXLM_Power_Down (.request/.response)***

The *WXLM_Power_Down.request* primitive is triggered by the upper layer to the WXLM to request a specific BS or SS/MN to power down. The *WXLM_Power_Down.response* primitive is sent by the WLXM with the WiMAX power down result.

The *WXLM_Power_Down* primitive's parameters are identified in Table 4-6.

Table 4-6: *WXLM_Power_Down (.request/.response)* – TMS primitive

WXLM Primitive	Description		
WXLM_Power_Down	*.request*	*primitive_id*	Unique ID for each primitive
		mac_addr	BS/SS/MN MAC Address
	.response	*primitive_id*	Unique ID for each primitive
		mac_addr	BS/SS/MN MAC Address
		result	Power down result

- ***WXLM_Power_Up (.request/.response)***

The *WXLM_Power_Up.request* primitive is triggered by the upper layer to the WXLM to request a specific BS or SS/MN to power up. The *WXLM_Power_Up.response* primitive is sent by the WLXM with the WiMAX power up result.

The *WXLM_Power_Up* primitive's parameters are identified in Table 4-7.

Table 4-7: *WXLM_Power_Up (.request/.response)* – TMS primitive

WXLM Primitive	Description		
WXLM_Power_Up	*.request*	*primitive_id*	Unique ID for each primitive
		mac_addr	BS/SS/MN MAC Address
	.response	*primitive_id*	Unique ID for each primitive
		mac_addr	BS/SS/MN MAC Address
		result	Power up result

4.3.3. WXLM QoS Management Service

WiMAX intrinsically supports QoS by using a connection-oriented approach, based on SFs and scheduling services. In the IEEE 802.16d standard, a SF is defined as a MAC transport service that provides unidirectional packet transport either for uplink or downlink. All packets traversing the MAC interface are associated with a SF, identified by a CID with some pre-defined treatment, and assigned resources for the duration of the connection. Several types of connections may be established in the IEEE 802.16 system, in particular, management, broadcast, multicast and transport connections, with associated QoS parameters [161] [162] [163].

A SF reservation process in the IEEE 802.16 system is shown in Figure 4-11, illustrating both the SFM primitives (*C-SFM-REQ* and *C-SFM-RSP*) in the C-SAP interface, as well the corresponding MAC management messages (*DSA-REQ*, *DSA-RSP* and *DSA-ACK*) in the IEEE 802.16 air interface.

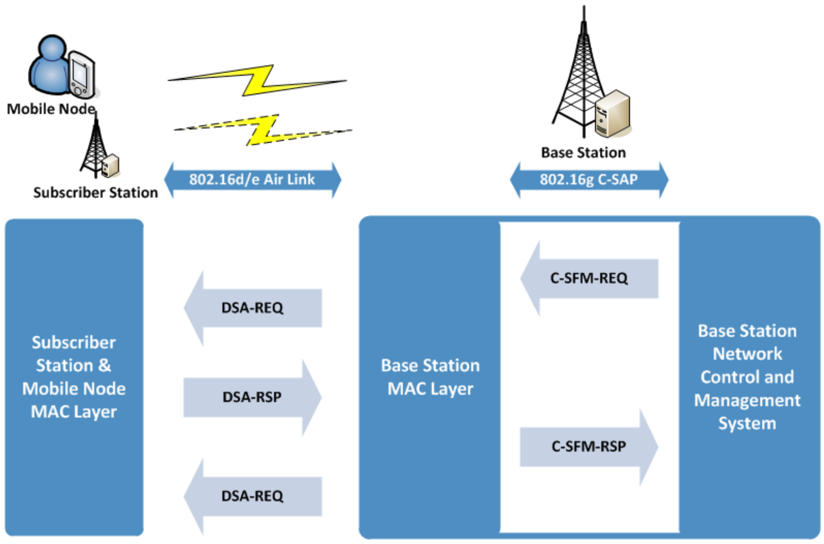

Figure 4-11: QoS procedures in IEEE 802.16 (d/e/g)

End-to-end QoS support needs to resort to a signaling protocol in order to convey the resource reservation requests along the network. The NSIS framework has been conceived in order to support network signaling, in general, with QoS signaling as its first application. The NSIS framework comprises two layers, namely, the GIST and the NSLP. The GIST is responsible for the transport of the signaling messages sent by NSLPs. The NSLP layer is specific to each application. The first NSLP defined, named QoS-NSLP, was designed to provide resource reservation signaling support. The QoS parameters specific for the QoS model of each context are defined on the QSPEC object defined in the NSIS framework. Depending on the context, the QoS parameters may vary. In order to establish an end-to-end resource reservation which crosses different domains and technologies, there is a need to map between the QoS parameters associated with each context. This function of QSPEC mapping may be performed horizontally and vertically. In the first case, the mapping is done between the QoS models of different domains. In the second case, also known as cross-layer, the mapping is performed between two different layers of the protocol stack, for instance, between the IP layer and the network access technology dependent layer.

By using the NSIS framework for end-to-end network signaling, and specifically, for resource reservation, we have to translate the IP QoS information conveyed by QoS-NSLP into the specific QoS parameters of the IEEE 802.16 technology. Although the IEEE 802.16g Network Control and Management System (NCMS) provides the C-SAP interface to manage IEEE 802.16 QoS, it does not define how to convert the generic QoS parameters from the upper layer entities and protocols to the IEEE 802.16 specific QoS parameters and scheduling services. Therefore, it is defined a new entity (QMS) responsible for abstracting and translating the generic QoS parameters to IEEE 802.16 specific QoS parameters.

The QMS controls all the QoS-related procedures of the WiMAX network, providing the upper layers QoS management entities with all the required functionalities to interact with the WiMAX system at the QoS level. It is responsible for handling WiMAX SFs, service classes and convergence sublayers, perform admission control on the WiMAX link, translate the generic layer 3 QoS parameters to WiMAX-compliant QoS parameters [153] [164].

Internally, as illustrated in Figure 4-12, the QMS is composed by the following set of modules: Service Flow Manager (SFM), Convergence Sublayer Manager (CSM), Admission Control Manager (ACM) and Service Class Manager (SCM).

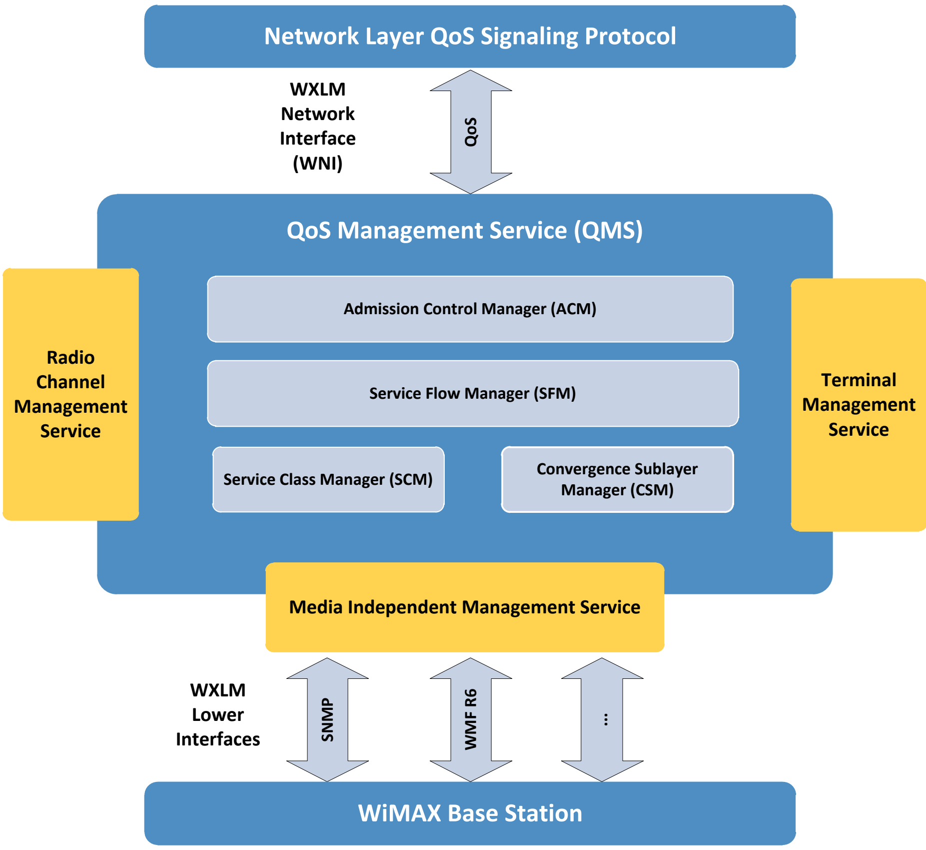

Figure 4-12: WXLM QoS Management Service (QMS) framework

The SFM is the most important function of the QMS, abstracting all the WiMAX QoS related decisions from the upper layers. It manages the SFs creation, modification and deletion, as well as the static (or provisioning) and dynamic SF reservation models, as described in [19]. Moreover, it triggers all the remaining functions of the QMS, such as the ACM, SCM and CSM. Moreover, it also contains repositories for the several types of SFs (provisioned, admitted and active) stored on the WiMAX link.

The main functions of the SFM are the following:

- Provide a generic and abstract QoS interface with the upper layer QoS entities abstracting the WiMAX technology details; further details about this interface are described in section 4.3.3.1;
- Manage the creation, modification and deletion of WiMAX SFs;
- Support for both IEEE 802.16d and IEEE 802.16e WiMAX versions;
- Support for the WiMAX QoS parameters (throughput, jitter, latency, priority) and scheduling services (UGS, ertPS, rtPS, nrtPS, BE);
- Support for the static (or provisioning) and dynamic WiMAX SFs reservation models;
- Manage the WiMAX SFs status and transitions;
- Maintain a repository with the WiMAX SFs;
- Interact and trigger the remaining functions of the QMS – SCM, CSM and ACM;
- Abstract the WiMAX equipment vendor specific details and enforce SFs decisions on the WiMAX equipment interacting with the MIMS, as described in section 4.3.5;

Besides managing the WiMAX SFs, the QMS also creates the requested Service Classes (SCs) through the SCM facilitating the SFs configuration on the WiMAX system.

The CSM is responsible for managing the classification rules for the WiMAX SFs [165]. The classification rules are based on a set of protocol-specific fields and are associates each (downlink and uplink) packet that crosses the WiMAX air link with a specific SF, which has a dedicated set of QoS parameters. The following CSs are supported:

- Ethernet Convergence Sublayer (EthCS): packet classification based on the source and destination MAC address, source and destination MAC mask, priority, …;
- IPv4 Convergence Sublayer (IPv4CS): packet classification based on the source and destination IPv4 address, source and destination IPv4 mask, Type-of-Service (ToS), IP protocol, source and destination port range, …;
- IPv6 Convergence Sublayer (IPv6CS): packet classification based on the source and destination IPv6 address, source and destination IPv6 mask, flow label, IP protocol, source and destination port range, … .

Each one of the aforementioned CSs information is stored in a dedicated repository controlled by the CSM.

The QMS is also responsible for deciding on new QoS requests through the ACM. The ACM verifies if the available resources in the WiMAX link are enough to satisfy the requirements of the new QoS request. If enough resources are available, the service reservation is accepted. On the other hand, if resources are not available to satisfy the requested QoS parameters, the ACM analyzes the SC and the Priority parameters from the new SF, and compares these parameters with the already existent SFs in the WiMAX link. Based on this evaluation, a lower priority SF can be downgraded, and hence the new QoS request is accepted, or the new QoS request is rejected. Information about the available resources on the WiMAX link is obtained through the RCMS, as illustrated in Figure 4-12.

4.3.3.1. QMS Primitives

Herein the QMS primitives defined for the WMI are described.

- ***WXLM_QoS_Resv (.request/.response)***

The *WXLM_QoS_Resv.request* primitive is triggered by the upper layer to the WXLM to request a QoS reservation towards a specific SS/MN. The *WXLM_QoS_Resv.response* primitive is sent by the WLXM with the WiMAX QoS reservation result.

The *WXLM_QoS_Resv* primitive's parameters are identified in Table 4-8.

Table 4-8: *WXLM_QoS_Resv (.request/.response)* – QMS primitives

WXLM Primitive	Description		
WXLM_QoS_Resv	*.request*	*primitive_id*	Unique ID for each primitive
		bs_mac_addr	BS to establish QoS reservation
		ss_mac_addr	SS/MN to establish QoS reservation
		sf_state	SF state (Provisioned, admitted, active)
		sched_serv	Scheduling Service (UGS, rtPS, ertPS, nrtPS, BE)
		max_rate	Maximum Sustained Bandwidth
		min_rate	Minimum Reserved Bandwidth
		max_latency	Maximum Latency
		sf_priority	Flow Priority
		jitter	Tolerated Jitter
		fix_var_sdu_size	SDU type (Fixed, variable)
		sdu_size	SDU size
		req_tx_policy	Request & transmission policy (BW request, piggyback, fragment, PHS, pack, CRC)
		dir	SF direction (Downlink, uplink)
		cs_classifier	Classifier information (IPv6, IPv4, Ethernet)
	.response	*primitive_id*	Unique ID for each primitive
		result	Reservation request result in the WiMAX equipment
		sf_id	SF identifier used in the WiMAX link

- ***WXLM_QoS_Mod (.request/.response)***

The *WXLM_QoS_Mod.request* primitive is triggered by the upper layer to the WXLM to request a QoS modification towards a specific SS/MN. The *WXLM_QoS_Mod.response* primitive is sent by the WLXM with the WiMAX QoS modification result.

The *WXLM_QoS_Mod* primitive's parameters are identified in Table 4-9.

Table 4-9: ***WXLM_QoS_Mod (.request/.response)*** **– QMS primitives**

WXLM Primitive	Description		
WXLM_QoS_Mod	*.request*	*primitive_id*	Unique ID for each primitive
		bs_mac_addr	BS to modify QoS reservation
		ss_mac_addr	SS/MN to modify QoS reservation
		sf_state	SF state (Provisioned, admitted, active)
		sched_serv	Scheduling Service (UGS, rtPS, ertPS, nrtPS, BE)
		max_rate	Maximum Sustained Bandwidth
		min_rate	Minimum Reserved Bandwidth
		max_latency	Maximum Latency
		sf_priority	Flow Priority
		jitter	Tolerated Jitter
		fix_var_sdu_size	SDU type (Fixed, variable)
		sdu_size	SDU size
		req_tx_policy	Request & transmission policy (BW request, piggyback, fragment, PHS, pack, CRC)
		dir	SF direction (Downlink, uplink)
		cs_classifier	Classifier information (IPv6, IPv4, Ethernet)
		sf_id	Service Flow identifier used in the WiMAX link
	.response	*primitive_id*	Unique ID for each primitive
		result	Modification request result in the WiMAX equipment
		sf_id	SF identifier used in the WiMAX link

- ***WXLM_QoS_Del (.request/.response)***

The *WXLM_QoS_Del.request* primitive is triggered by the upper layer to the WXLM to request a QoS deletion towards a specific SS/MN. The *WXLM_QoS_Del.response* primitive is sent by the WLXM with the WiMAX QoS deletion result.

The *WXLM_QoS_Del* primitive's parameters are identified in Table 4-10.

- ***WXLM_QoS_AC (.request/.response)***

The *WXLM_QoS_AC.request* primitive is triggered by the upper layer to request the WXLM to perform admission control for a specific QoS request. As a result, the *WXLM_QoS_AC.response* primitive is sent by the WLXM with the admission control result.

The *WXLM_QoS_AC* primitive's parameters are identified in Table 4-11.

Table 4-10: *WXLM_QoS_Del (.request/.response)* – QMS Primitives

WXLM Primitive	Description		
WXLM_QoS_Del	*.request*	*primitive_id*	Unique ID for each primitive
		bs_mac_addr	BS to delete SF
		ss_mac_addr	SS/MS to delete SF
		sf_id	Service Flow identifier used in the WiMAX link
	.response	*primitive_id*	Unique ID for each primitive
		result	Deletion request result in the WiMAX equipment
		sf_id	SF identifier used in the WiMAX link

Table 4-11: *WXLM_QoS_AC (.request/.response)* – QMS primitives

WXLM Primitive	Description		
WXLM_QoS_AC	*.request*	*primitive_id*	Unique ID for each primitive
		bs_mac_addr	BS to establish QoS reservation
		ss_mac_addr	SS/MN to perform admission control
		sf_state	SF state (Provisioned, admitted, active)
		sched_serv	Scheduling Service (UGS, rtPS, ertPS, nrtPS, BE)
		max_rate	Maximum Sustained Bandwidth
		min_rate	Minimum Reserved Bandwidth
		max_latency	Maximum Latency
		jitter	Tolerated Jitter
		fix_var_sdu_size	SDU type (Fixed, variable)
		sdu_size	SDU size
		req_tx_policy	Request & transmission policy (BW request, piggyback, fragment, PHS, pack, CRC)
		dir	SF direction (Downlink, uplink)
	.response	*primitive_id*	Unique ID for each primitive
		result	Reservation request result in the WiMAX equipment

4.3.4. WXLM Radio Channel Management Service

The IEEE 802.16 standard provides a set of functionalities to retrieve information about the link quality and the available radio resources in the WiMAX link. In detail, the NCMS defines the Radio Resource Management (RRM) service, which defines the *Control Radio Resource Management Request (C-RRM-REQ)*, *Response (C-RRM-RSP)* and *Indication (C-RRM-IND)* primitives to obtain the aforementioned information. In what concerns the link quality information, the RRM service triggers the *C-RRM-REQ* towards the MAC layer to get information about the Carrier to Interference Noise Ratio (CINR) and received Signal Strength Indicator (RSSI) levels. Thereafter, the IEEE 802.16 BS MAC layer triggers the *Report Request (REP-REQ)* MAC management message towards the WiMAX terminal and receives a *REP-RSP* message. Finally, the *C-RRM-RSP* primitive is sent back to the NCMS with the link layer information (CINR and RSSI). This procedure is illustrated in Figure 4-13.

The *C-RRM-REQ/RSP* primitives can also be used by the NCMS to get information about the resources availability on the WiMAX BS. Furthermore, as illustrated in the bottom of Figure 4-13, the *C-RRM-IND* is used by the BS MAC layer to send periodically or event-driven radio resources availability on the WiMAX link.

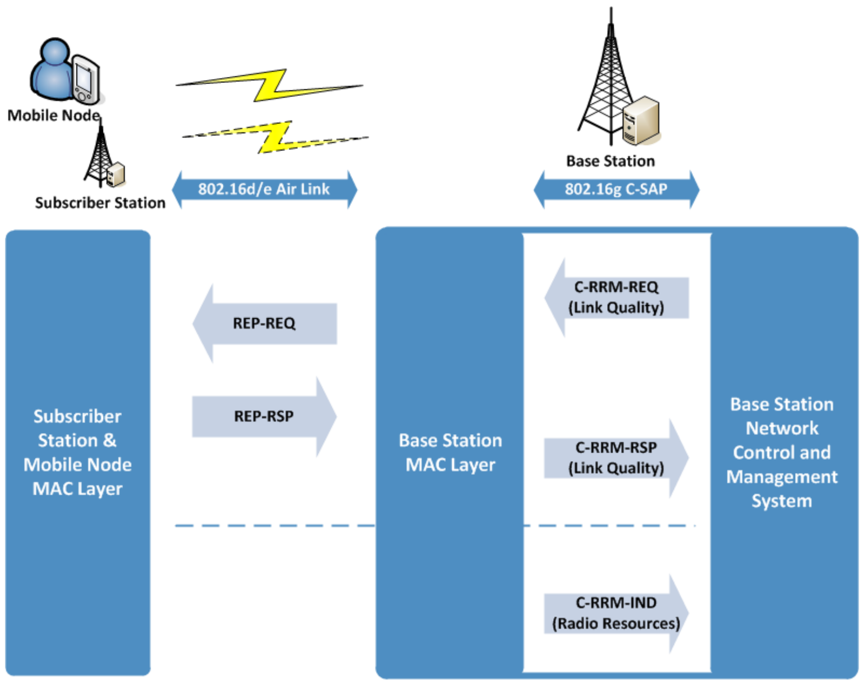

Figure 4-13: Radio channel management procedures in IEEE 802.16 (d/e/g)

To handle the radio link information provided by the WiMAX system, the WXLM defines the RCMS. The RCMS is responsible for managing the information related with the physical layer of the WiMAX link. The retrieved information from the WiMAX link can be related with the most relevant physical layer parameters, such as the CINR, the RSSI, an estimation of the available radio resources on the WiMAX link, as well as data related measurements (for example data error rate). This information is collected for the uplink and for the downlink of the WiMAX channel.

Figure 4-14 illustrates the RCMS internal architecture, composed by the Radio Resource Manager (RRM), the Link Quality Manager (LQM) and the Radio Configuration Manager (RCM).

The RRM collects radio resources information from the BS and assists the remaining WXLM services, such as the QMS and the MMS, which require information about the resources availability on the WiMAX link to apply their actions. The available resources are a function of the percentage of average available sub-channels and symbols resources per frame.

One example for the RRM importance in the overall WXLM system is to assist the admission control procedures of the QMS. The retrieved resources information is crucial for performing MNs and SFs admission control, that is, to permit or reject the creation (or modification) of SFs on the WiMAX link. Cooperation and information exchange between the RCMS, in this case the RRM, and the QMS is therefore required for admission control purposes.

Another example of the importance of the RRM is related with load balancing control and management between WiMAX BSs. Providing information about the radio resources from a specific BS to the QMS enables the later to take actions when the required resources for a specific connection is not being delivered. In this case load control can be applied depending on the configured policies, as well as on the MN contract with the network operator. Another option to control the excessive load on a specific BS is to balance the data to another BS. In other words, since the RCMS provides information about the resources occupancy on the set of BSs that belong to a specific ASN-GW, the QMS has a global view about the ASN resources. Therefore it can trigger the WXLM MMS, described in chapter 5, to activate the required mobility procedures to a neighbor WiMAX BS and therefore balance the load between BSs. In this case three services from the WXLM are directly involved: RRM to assess the radio resources, QMS to control the load and the MMS to perform handover.

Depending on the configuration performed by the RRM on the BS, the resources indicators retrieved by the RRM from the BS can be obtained in one of three options:

- Solicited: the RRM requests the WiMAX BS to provide the radio resources availability immediately;
- Periodic: the RRM configures the WiMAX BS to provide the radio resources availability periodically. The information is provided by the BS in specific time-slots indicated by the RRM;
- Event-driven: the RRM configures the WiMAX BS to provide the radio resources availability when a specific event occurs. In this case, the BS provides the resources information when a specific configured threshold value of the available resources is surpassed.

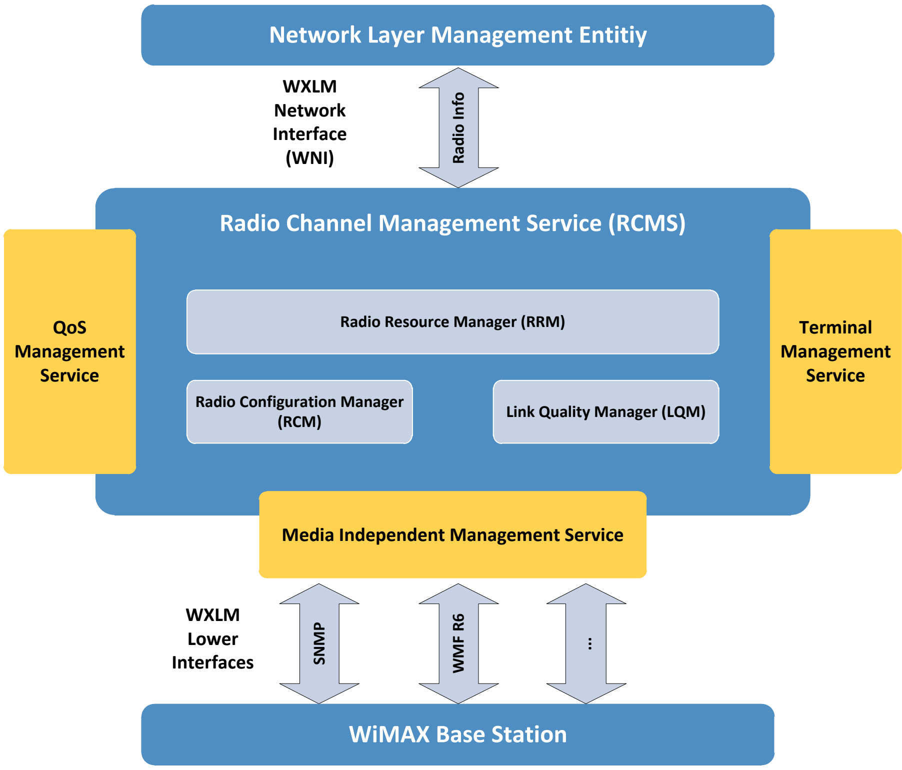

Figure 4-14: WXLM Radio Channel Management Service (RCMS) framework

With respect to the LQM, it is responsible to assess the quality of the WiMAX link for each SS/MN, in both downlink and uplink directions. Specifically, the link information – CINR and RSSI – is retrieved from the WiMAX channel for the serving BS and for the candidate BSs surrounding the SS/MN. The uplink information is retrieved directly from the WiMAX BS, whereas the download information has to be retrieved from the SS/MN.

The information obtained by the LQM is important to select the most suitable candidate WiMAX BS during a handover procedure. Thus the LQM cooperates directly with the MMS.

Finally, the RCM is responsible for configuring radio (e.g. channel frequency, transmission power, …), physical (e.g. channel size, guard interval, …) and MAC (e.g. frame duration, downlink frame ratio, …) parameters of the WiMAX BS during the system setup.

With respect to the RCMS interactions with the other WXLM services, as described in the previous paragraphs, it interacts with the QMS for admission control purposes and with the MMS for handover preparation and control scenarios. Nevertheless, the cooperation with other WXLM services is not limited to the QMS and the MMS. The RCMS also communicates with the TMS to obtain information about the IEEE 802.16d and IEEE 802.16e network topology, enabling the RCMS to acquire the resources availability information, either through a query process or through an event-driven process. Finally, to enable a vendor independent communication with the WiMAX BS, the RCMS utilizes the functionalities provided by the MIMS.

4.3.4.1. RCMS Primitives

Herein the RCMS primitives defined for the WNI are described.

- ***WXLM_Thresholds_Config (.request/.response)***

The *WXLM_Thresholds_Config.request* primitive is triggered by the upper layer to configure the radio link thresholds or to specify the times interval between periodic reports. The *WXLM_Thresholds_Config.response* primitive is sent by the WLXM towards the upper layers with the threshold configuration result.

The *WXLM_Thresholds_Config* primitive's parameters are identified in Table 4-12.

Table 4-12: *WXLM_Thresholds_Config (.request/.response)* – RCMS primitives

WXLM Primitive	Description		
WXLM_Thresholds_Config	*.request*	*primitive_id*	Unique ID for each primitive
		bs_mac_addr	BS to configure the thresholds
		ss_mac_addr	SS/MN to configure thresholds
		report_type	Periodic or event-driven notifications
		report_interval	Notifications report interval
		cinr	Threshold value for the CINR
		rssi	Threshold value for the RSSI
		resources	Threshold value for the resources
	.response	*primitive_id*	Unique ID for each primitive
		result	Parameters configuration result in the WiMAX equipment

- ***WXLM_Parameters_Report (.indication)***

The *WXLM_Parameters_Report.indication* primitive is triggered by the WXLM towards the upper layer with information about the WiMAX BS available radio resources and the SSs/MNs downlink and uplink CINR and RSSI.

The *WXLM_Parameters_Report* primitive parameters are identified in Table 4-13.

Table 4-13: *WXLM_Parameters_Report (.indication)* – RCMS primitive

WXLM Primitive	Description		
WXLM_Parameters_Report	*.indication*	*primitive_id*	Unique ID for each primitive
		bs_mac_addr	BS that is providing the report
		ss_mac_addr	SS/MN that is providing the report
		cinr	CINR value
		rssi	RSSI value
		resources	Radio resources value

- ***WXLM_Get_Parameters (.request/.response)***

The *WXLM_Get_Parameters.request* primitive is triggered by the upper layer to request for the radio channel parameters (radio resources, CINR, RSSI). The *WXLM_Get_Parameters.response* primitive is sent by the WLXM towards the upper layers with the required parameters retrieval.

The *WXLM_Get_Parameters* primitive's parameters are identified in Table 4-14.

Table 4-14: *WXLM_Get_Parameters (.request/.response)* – RCMS primitives

WXLM Primitive	Description		
WXLM_Get_Parameters	*.request*	*primitive_id*	Unique ID for each primitive
		bs_mac_addr	BS to get parameters
		ss_mac_addr	SS/MN to get parameters
	.response	*primitive_id*	Unique ID for each primitive
		cinr	CINR value
		rssi	RSSI value
		resources	Radio resources value

4.3.5. WXLM Media Independent Management Service

To cope with the complexity that the increasing heterogeneity brings into future communication networks, the MIMS is defined by the WXLM, which provides a common solution that applies to different WiMAX vendor equipments. This service provides architecture independence, as much as possible, from the WiMAX equipments manufacturers. Achieving this level of independency permits that different WiMAX equipments can be seamlessly integrated and supported without requiring modifications over the remaining architecture modules and interfaces. Figure 4-15 illustrates the MIMS.

The MIMS is composed by the GA module and one or more VSAs. The GA allows the convergence between different VSAs for the adaptive applications and processes. The GA provides an abstraction of the hardware management functions. All details are hidden from the upper modules, allowing the use of common primitives. To allow this, the GA converts the common primitives to more specific primitives, serving the needs of the vendor specific adapters. GA is able to communicate with local and remote VSA modules using inter-process communication.

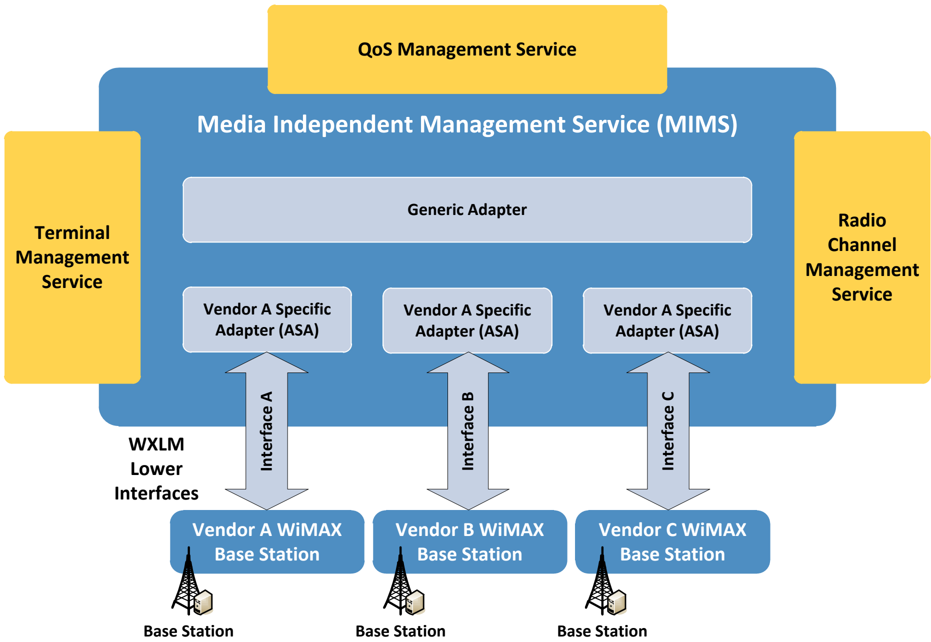

Figure 4-15: WXLM Media Independent Management Service (MIMS) framework

4.3.5.1. Redline Communications Specific Adapter

The VSA deals with the WiMAX equipment specificities. For each vendor specific equipment, a library is implemented providing a differentiated request-response processing, according to the supported protocol by the WiMAX system (SNMP, HTTP, Telnet, WiMAX Forum R6, …). Each VSA is responsible to fetch information from the WiMAX network elements (allowing important control functions, such as admission control and effective resources control) and to enforce the control decisions triggered by upper layer entities in the WiMAX segment. Hence, its functionalities assume considerable relevance in the global architecture. Summarizing, in order to support an additional WiMAX vendor equipment in the WXLM system, minor modifications are required. More precisely, it is only necessary to design and implement a new VSA, as well as the associated interface without modifying any other module or interface.

Within the WEIRD project, four different VSAs were implemented and tested with this architecture. The Airspan, Redline Communications, Alvarion, and Alcatel VSAs have been implemented to interface with each associated WiMAX BS. The Redline Communications Specific Adapter (RCSA) was implemented in the scope of this thesis to interface with the Redline Communications WiMAX equipment.

The RCSA, illustrated in Figure 4-16, interfaces with the Redline Communications WiMAX BS enforcing QoS requests from the upper layer modules following the IEEE 802.16f Management Information Base (MIB) standard [166]. The RCSA also retrieves resource and topology information from the Redline BS. The interface between the RCSA and the WiMAX BS is established using the SNMP protocol when communicating with the SNMP agent module of BS, and alternatively the proprietary CLI/Telnet interface, when the SNMP interface is not available. The RCSA SNMP interface was implemented using the open-source Net-SNMP API [167], whereas the CLI/Telnet interface was implemented through automated scripts. The RCSA is responsible for three main functionalities:

- Service flow management: refers to managing and enforcing the received QoS reservations, modifications and deletions requests in the Redline WiMAX equipment, either using IPv4 or 802.3 CSs;
- Resources management: shows in the aptitude to answer upon resource requests collecting information from the IEEE 802.16 network as RF, PHY and MAC parameters, including downlink and uplink available bandwidth for the SSs/MNs, and packing that information to the higher layer management entities;
- Dynamic IEEE 802.16 network discovery: consists on the ability to detect new SSs/MNs and BSs that join the WiMAX network. The complete network topology of the WiMAX segment is built in a

dynamic way, supplying at the same time relevant PHY and MAC parameters to the NMS. This WiMAX network discovery feature is implemented over the SNMP traps supported by the Redline WiMAX equipment.

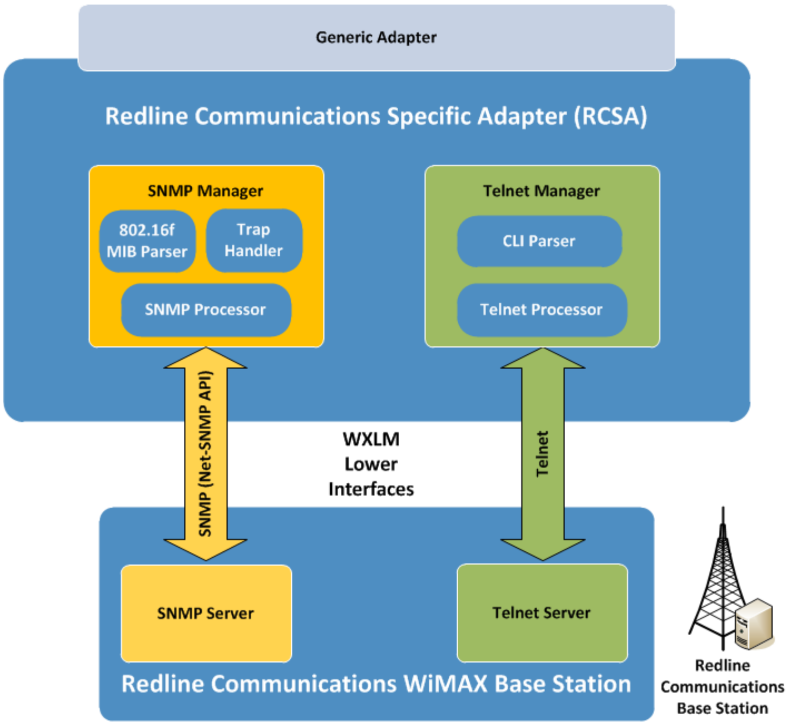

Figure 4-16: High-level architecture of the Redline Communications Specific Adapter (RCSA)

The next section provides detailed message-sequence charts about the WXLM services interaction and operation in the overall QoS procedure.

4.4. WiMAX Cross Layer Manager Signaling Diagrams

This section provides a set of detailed signaling diagrams proposed within this Thesis to illustrate the WXLM services integration in the proposed WiMAX QoS-enabled architecture. The IP level signaling messages, more precisely NSIS and SIP were obtained from the WEIRD project. The following scenarios are depicted:

1. WiMAX BS network entry procedure (section 4.4.1);
2. WiMAX SS/MN network entry (section 4.4.2);
3. Real-time QoS Management for SIP applications in a single-ASN scenario (section 4.4.3.2);
4. Real-time QoS Management for SIP applications in a double-ASN scenario (section 4.4.3.1);
5. Real-time QoS Management for legacy applications (section 4.4.4);

Figure 4-17 illustrates the set of scenarios depicted in the following sub-sections.

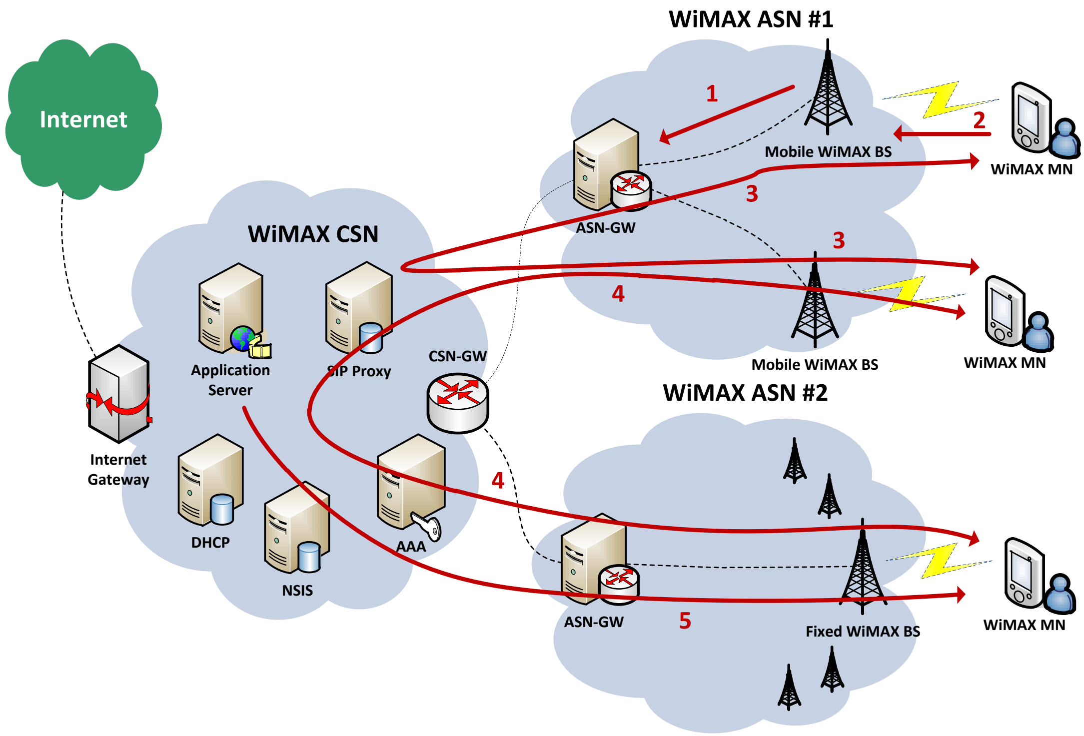

Figure 4-17: Signaling diagrams

4.4.1. WiMAX BS Network Entry

Herein it is described a network entry procedure for a WiMAX BS. Detailed signaling procedures are provided for all the architecture entities involved, namely the WiMAX BS, the WXLM, the CSC_ASN and the NMS, with special focus on the WXLM services. The detailed message sequence chart is illustrated in Figure 4-18, and explained as follows:

Step 1:

- After the BS is connected, the NMS triggers a *New_BS.ind* message towards the CSC_ASN;
- The CSC_ASN informs the WXLM through a *WXLM_New_BS.ind*;
- Thereafter the WXLM TMS detects that a new WiMAX BS is connected and updates the network topology database.

Step 2:

- The WXLM RCMS configures the WiMAX BS thresholds to retrieve information about the radio resources availability by sending the WiMAX Forum R6 message *RRM_Spare_Capacity.req* towards the BS (using the WXLM MIMS). If the WiMAX Forum R6 interface is not supported by the BS, the WXLM MIMS has the capability to support any other interface, such as SNMP, as described in section 4.3.5.1 for the RCSA.

Step 3:

- The CSC_ASN sends a *WXLM_QoS_Resv.req* message towards the WXLM to configure the provisioned SFs (retrieved from the NMS);
- The WXLM QMS triggers the MIMS to communicate the reservation request to the WiMAX BS; this can be done using either the R6 interface message *RR.req* or through the SNMP message *SNMP_Set*.

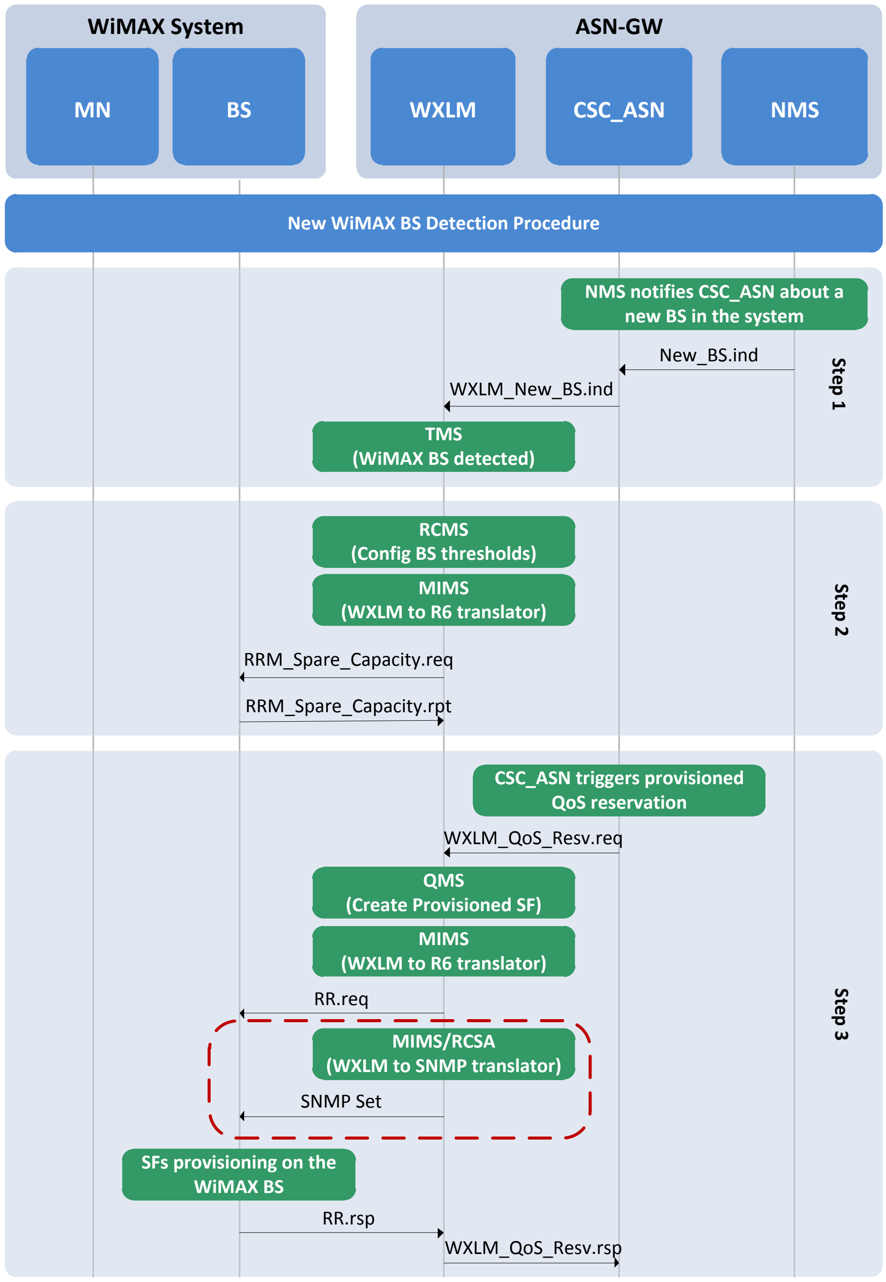

Figure 4-18: WiMAX BS detection

After the BS is connected and configured, it is prepared to receive WiMAX terminals. This procedure is described in the following section.

4.4.2. WiMAX SS/MN Network Entry

This case describes the signaling procedure for a WiMAX terminal (fixed and/or mobile) joining the network (Figure 4-19).

Step 1:

- The AAA notifies the CSC_ASN that a new MN is joining the network;
- The CSC_ASN notifies the WXLM TMS that a new MN is connecting (*WXLM_New_MN.ind*).

Step 2:

- The WXLM configures the WiMAX system to retrieve information about the terminal link quality, specifically the CINR and RSSI, in the uplink and downlink directions, through the RCMS (WiMAX Forum R6 message *PHY_Parameters.req*);
- The uplink direction information is directly obtained from the BS, whereas the downlink information is obtained from the SS/MN using the WiMAX MAC management messages depicted in section 4.3.4 – *REP-REQ/RSP* and *C-RRM-REQ/RSP*.

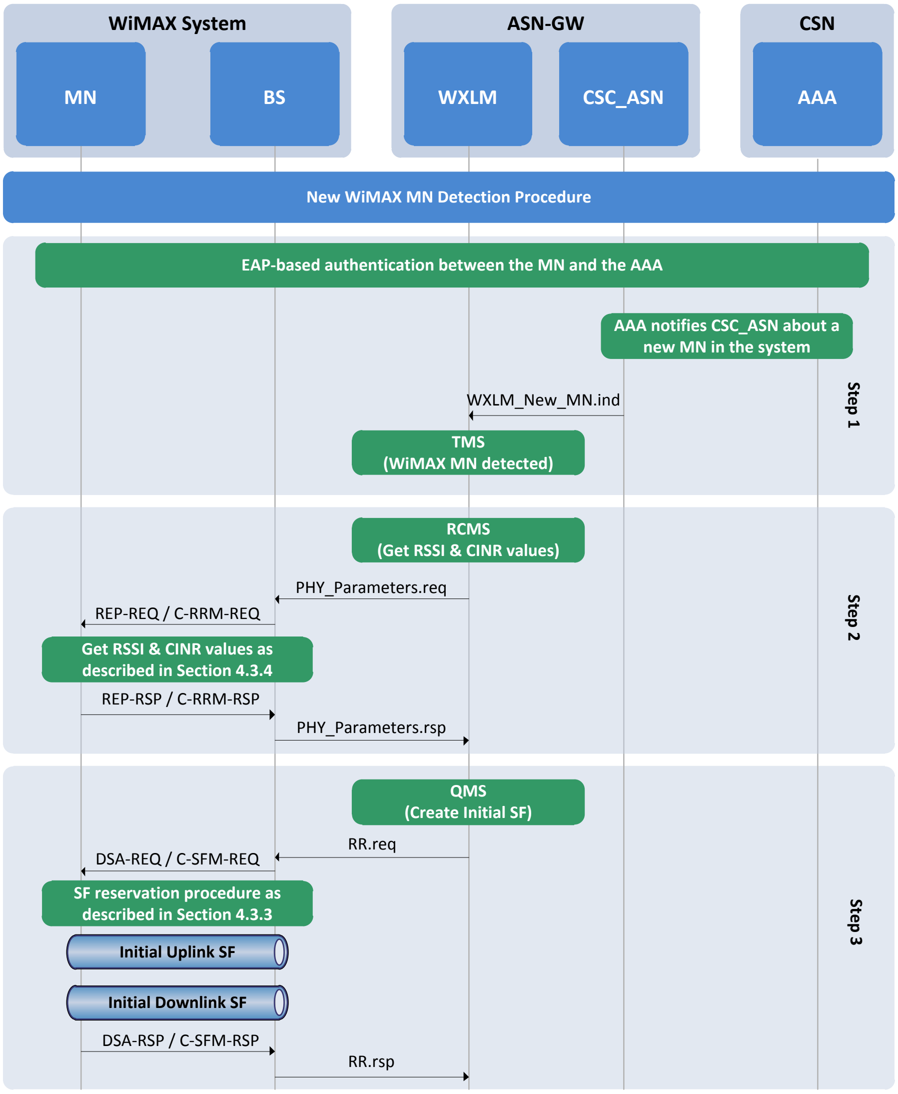

Figure 4-19: WiMAX SS/MN detection

Step 3:

- After detecting and configuring the WiMAX system reporting thresholds, the WLMX QMS will establish the required QoS reservations in the WiMAX link to allow signaling messages to traverse the wireless link;
- The QMS prepares the QoS parameters, convergence sublayers and service classes required to establish the Initial SF (ISF) on the WiMAX link;
- Thereafter, using the functionalities provided by the MIMS, triggers the WiMAX BS and establishes the WiMAX ISF using the *RR.req* message;

- Finally, on the BS side, the required MAC management messages to activate the ISF follow the procedure described in section 4.3.3 – *DSA-REQ/RSP* and *C_SFM_REQ/RSP*.

The next step is to activate the negotiated provisioned SFs on the WiMAX BS. The QMS is responsible for checking if the recently connected MN has provisioned SFs. If the QMS detects provisioned SFs, it triggers their reservation in the WiMAX link using a similar procedure as the one used for the ISF allocation.

At this point the WiMAX user is able to receive and/or send signaling and provisioned data packets through the air link. Nevertheless, it is still not ready to allow real-time applications, such as VoIP and video applications, to exchange packets. The following section addresses this issue for multimedia and legacy applications.

4.4.3. Real-time QoS Management for SIP Applications

This section depicts a signaling procedure for real-time applications, which require dynamic end-to-end QoS management. In order to support legacy and SIP-aware applications, two signaling protocols are supported in the proposed architecture – NSIS and SIP as described in sections 4.2.2 and 4.2.3, respectively. Herein we will describe the integration of the SIP protocol for single-ASN (section 4.4.3.1) and double-ASN scenarios (section 4.4.3.2) with the WXLM services.

The SIP protocol adopts the two-phase activation model in the WiMAX link, that is, during the SIP call establishment the required SFs are only admitted without data, and these SFs are activated when the SIP call negotiation capabilities are finished. The following procedures illustrate the WXLM signaling procedures for a SIP call, including the aforesaid two activation phases.

4.4.3.1. SIP Single-ASN Scenario

In this scenario the caller and the callee are located on the same WiMAX ASN, and therefore the data path in the CSN is not modified (Figure 4-20 and Figure 4-21).

Step 1:

- The SIP proxy intercepts the SIP *Invite* message received from the SIP UA to establish the call;
- The SIP proxy authenticates the user in the AAA server using the *MAR/MAA* messages from the Diameter protocol;
- After successful authentication, the SIP proxy triggers an intermediate QoS reservation (considering the worst-case bandwidth requirements) in the WiMAX network (BS#1 and BS#2) through the CSC_ASN – the *AAR/AAA* messages from the Diameter protocol are used by the SIP proxy to interface with the CSC_ASN;
- The CSC_ASN queries the AAA for authorization on the QoS parameters requested for the user – done using the *QAR/QAA* Diameter messages.

Step 2:

- The CSC_ASN queries the WXLM QMS to check if enough resources are available – Admission Control (AC) procedures using the *WXLM_QoS_AC.req* message;
- The WXLM RCMS checks for resources availability (*RRM_Spare_Capacity.req*);
- The CSC_ASN also checks for resources availability on the wired link between the BS and ASN-GW;
- If resources are available on both the wired and wireless WiMAX links, the CSC_ASN triggers the WXLM QMS to reserve uplink and downlink SFs in the admitted state. This reservation procedure is identical to the one described in section 4.4.2 for the ISF;
- This procedure is repeated for both BS#1 and BS#2, connected to the same ASN-GW.

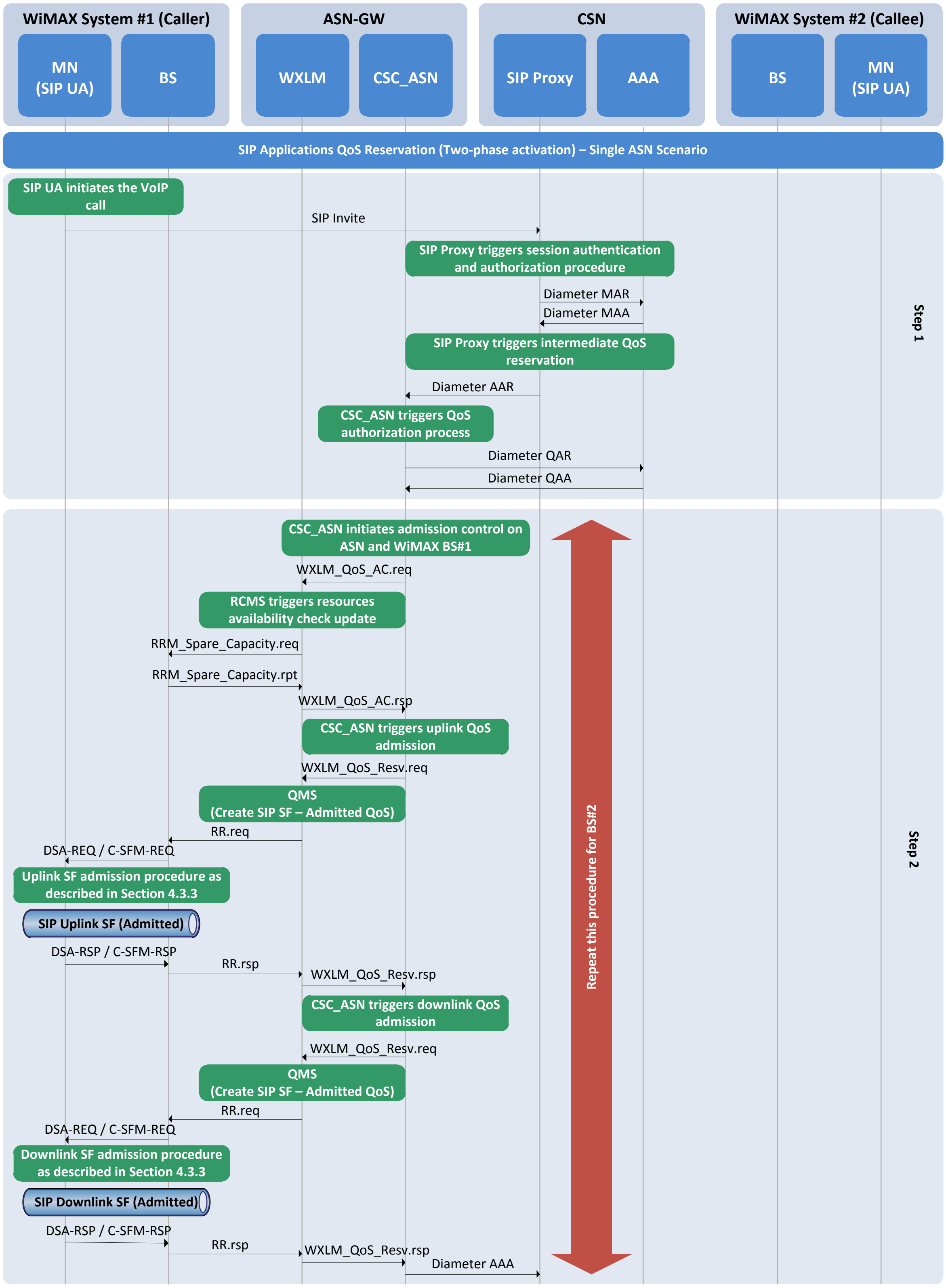

Figure 4-20: WiMAX QoS management for SIP applications – single-ASN scenario (I)

Step 3:

- The SIP signaling proceeds and when the SIP proxy receives the *200 OK* message, the negotiated QoS parameters are available in the SDP message.

Step 4:

- The CSC_ASN triggers the WXLM QMS to activate the admitted SFs with the correct QoS parameters (*WXLM_QoS_Resv.req*);
- The WXLM QMS communicates the decision to the WiMAX BS through the *RR.req* and the SFs are modified using the *DSC-REQ/RSP* and *C-SFM-REQ/RSP* messages;
- This procedure is repeated for both BS#1 and BS#2.

Step 5:

- SIP signaling is completed (SIP *200 OK* towards the caller);
- Multimedia session starts between caller and callee located in the ASN.

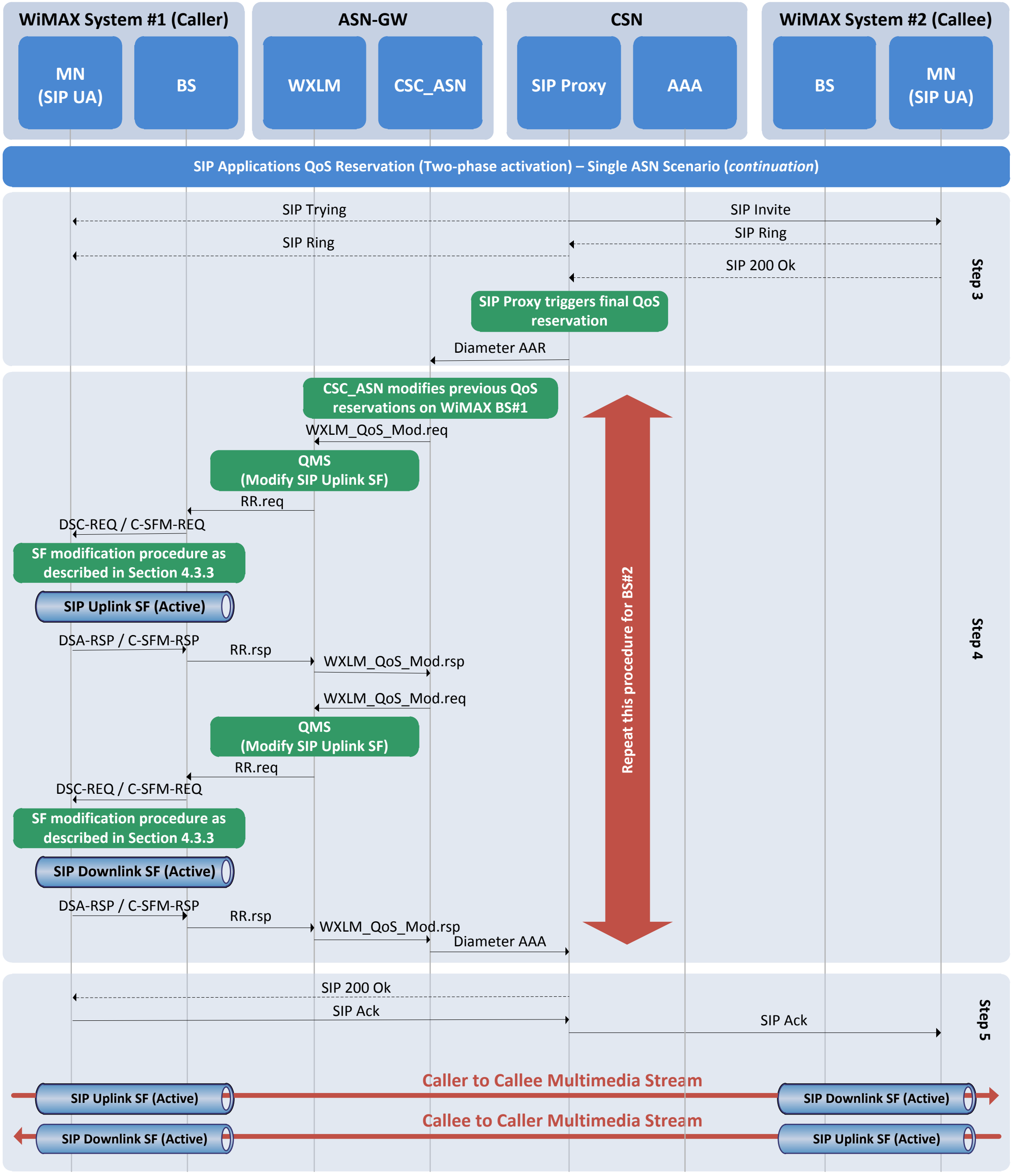

Figure 4-21: WiMAX QoS management for SIP applications – single-ASN scenario (II)

4.4.3.2. *SIP Double-ASN Scenario*

In this scenario the caller and the callee are located on different WiMAX ASNs and therefore the data path in the CSN is modified (Figure 4-22, Figure 4-23 and Figure 4-24). The authentication, the QoS authorization and the SF admission and activation are very similar to the previous ones, but in this scenario resources need to be reserved also in the CSN and in the CN.

Step 1:

- The SIP proxy intercepts the SIP *Invite* message received from the SIP UA to establish the call;
- The SIP proxy initiates session authentication and authorization, as well QoS authorization as described in the single-ASN scenario step 1 (section 4.4.3.1).

Step 2:

- CSC_ASN#1 initiates resources query on the caller to callee direction for CSN and CN using the NSIS protocol messages (*NSIS_Query_Req*); the CSC_ASN acts a QNI and creates the initiator QSPEC according to the WiMAX QoS model;
- The next NSIS peer, located in the CSN, is an edge node situated between two different domains, a WiMAX domain and, for example, a DiffServ domain, and hence supports both QoS models. This NSIS peer is in charge of the translation of the WiMAX QSPEC into the DiffServ QSPEC;
- CSC_ASN#1 initiates resources AC and admission on the ASN#1 and BS#1, as described in the single-ASN scenario step 2 (section 4.4.3.1).

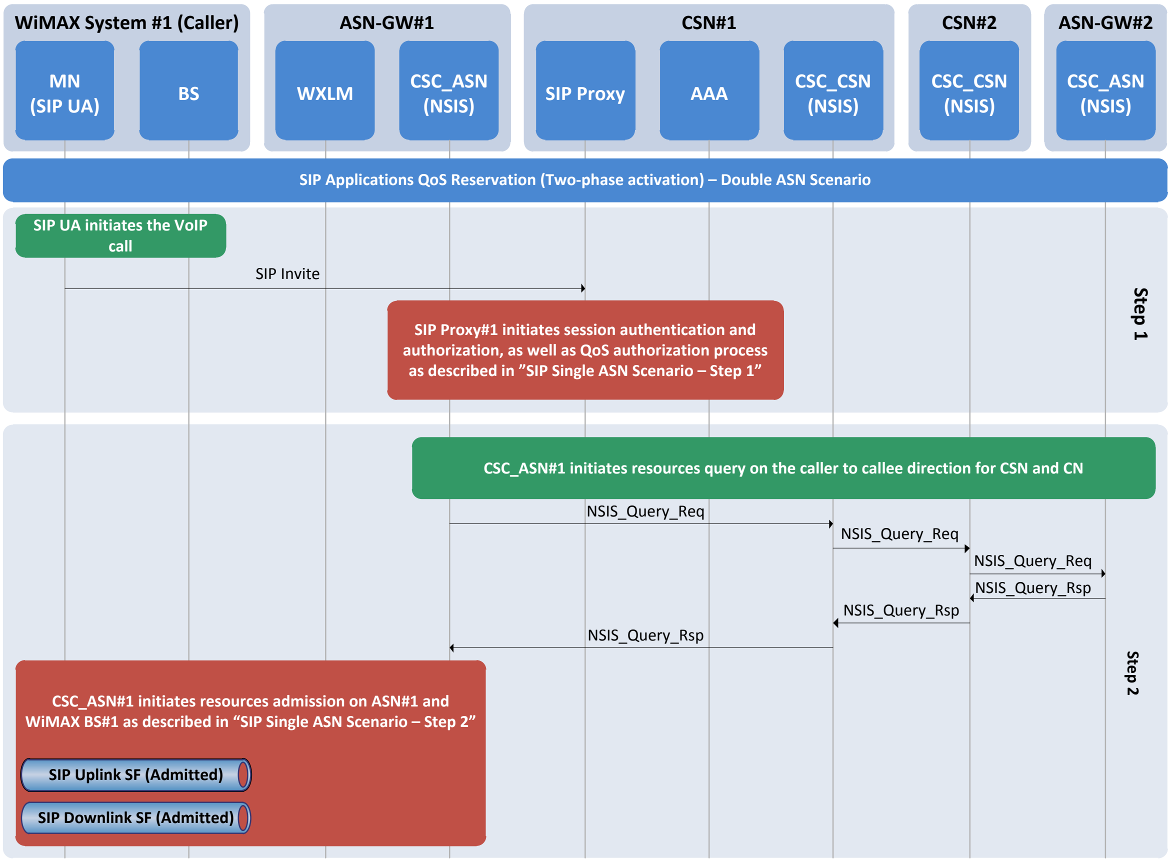

Figure 4-22: WiMAX QoS management for SIP applications – double-ASN scenario (I)

Step 3:

- The SIP signaling (SIP *Invite*) proceeds towards SIP proxy #2;

- CSC_ASN#2 verifies the resources availability on the callee to caller direction using the *NSIS_Query_Req* (as in step 2 but for a different direction);
- CSC_ASN#2 initiates resources AC and admission on the ASN#2 and BS#2; the process is similar to the one described in step 2.

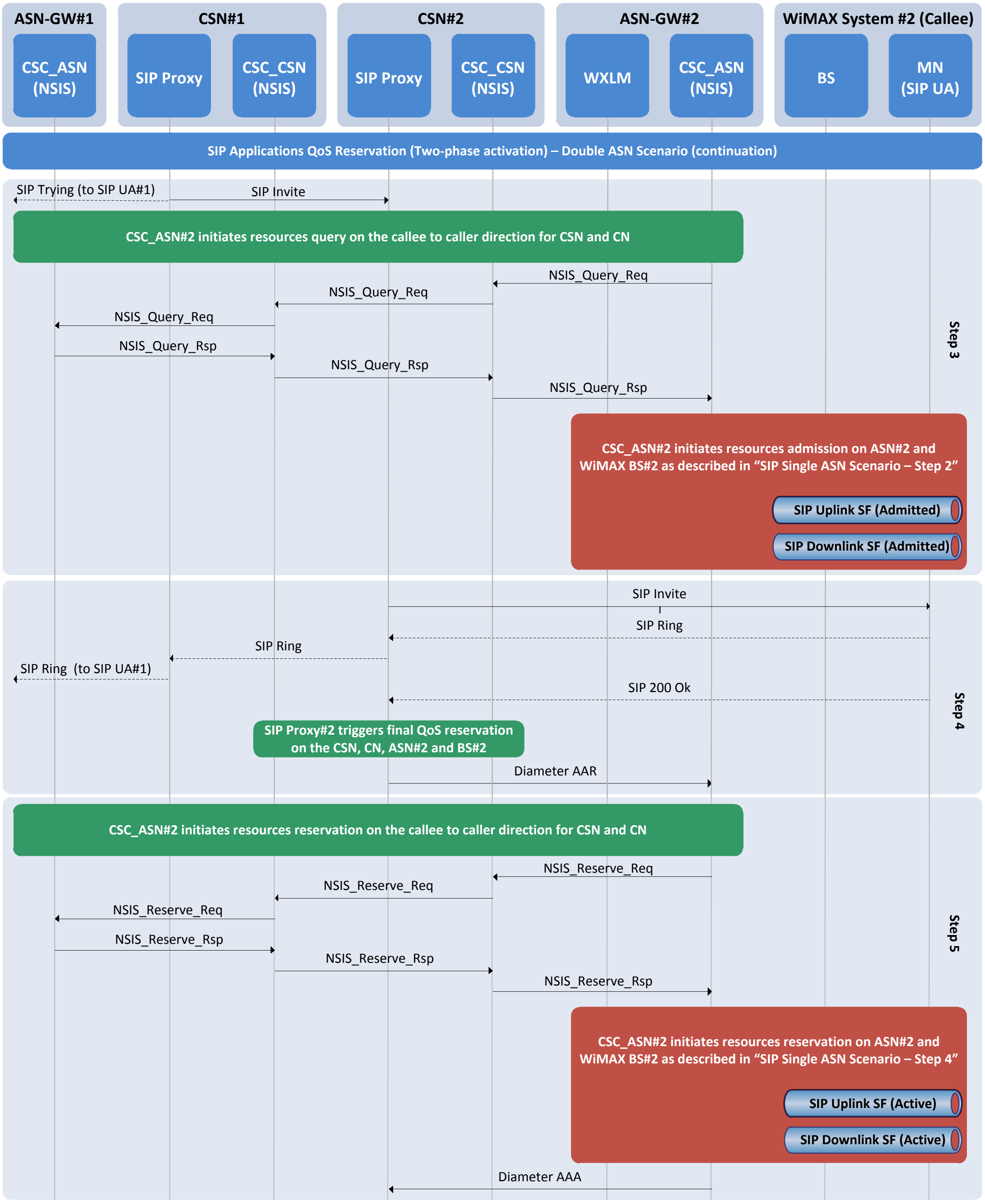

Figure 4-23: WiMAX QoS management for SIP applications – double-ASN scenario (II)

Step 4:

- The SIP signaling proceeds and when the SIP proxy receives the *200 Ok* message, the negotiated QoS parameters are available in the SDP message;

- The SIP proxy #2 triggers the correct QoS reservation on the CN, CSN#2, ASN#2 and BS#2.

Step 5:

- CSC_ASN#2 initiates resources reservation on the callee to caller direction for CSN#2 and CN using the NSIS protocol messages (*NSIS_Reserve_Req*); the QSPEC included in the NSIS messages contains the correct values for the bandwidth, as negotiated between the two agents with the SIP signaling, so only the strictly required bandwidth is actually allocated;
- CSC_ASN#2 initiates resources activation on the ASN#2 and BS#2, as described in the single-ASN scenario step 4 (section 4.4.3.1).

Step 6:

- The SIP signaling (*SIP 200 Ok*) proceeds towards SIP proxy #1;
- The SIP proxy #1 triggers the correct QoS reservation on the CN, CSN#1, ASN#1 and BS#1.

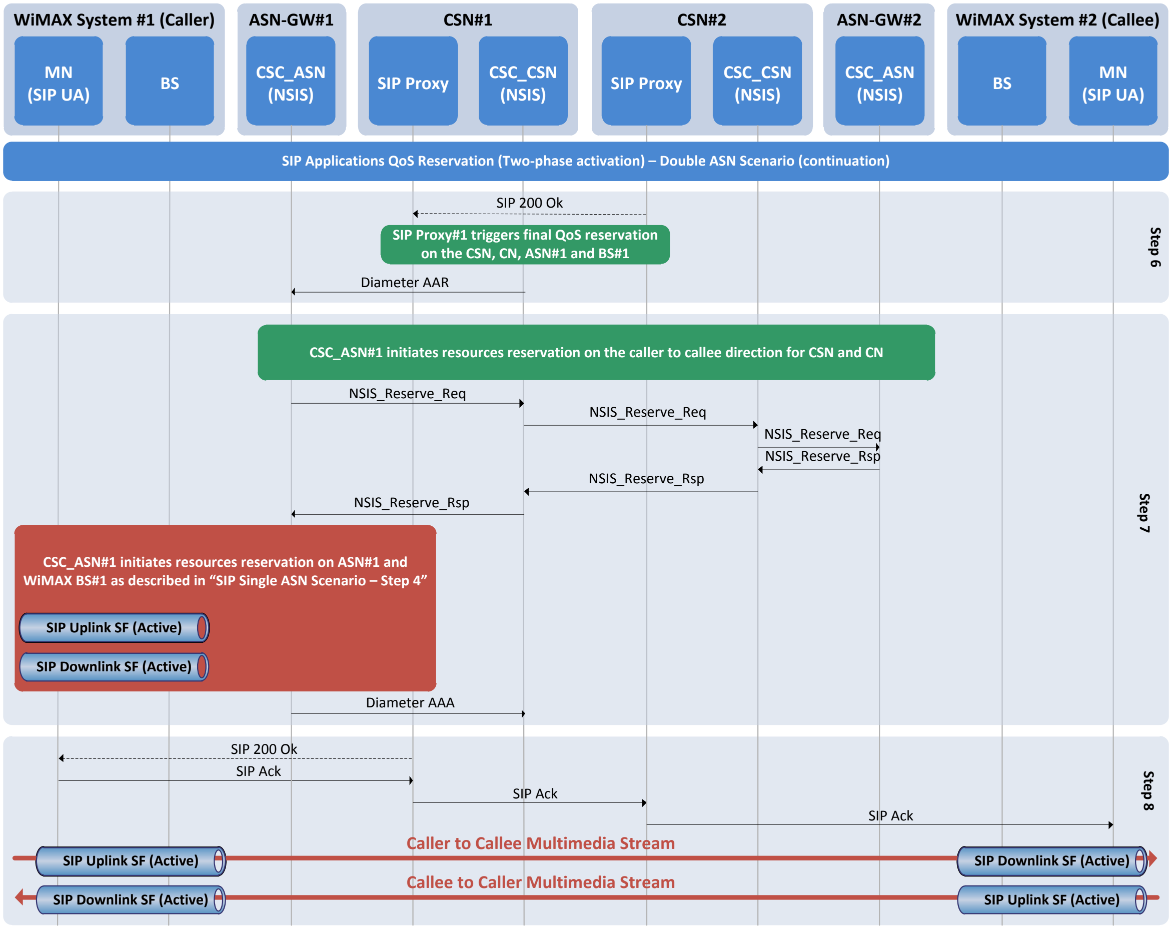

Figure 4-24: WiMAX QoS management for SIP applications – double-ASN scenario (III)

Step 7:

- CSC_ASN#2 initiates resources reservation on the caller to callee direction for CSN#1 and CN using the *NSIS_Reserve_Req* message;
- CSC_ASN#2 initiates resources activation on the ASN#1 and BS#1, as described in step 5.

Step 8:

- SIP signaling is completed (*SIP 200 Ok* towards the caller);

- Multimedia session starts between caller and callee on different ASNs.

4.4.4. Real-time QoS Management for Legacy Applications

This section describes the QoS signaling procedure for legacy applications. Figure 4-25 illustrates the set of required steps from the moment that the legacy application triggers the resources reservation procedure until multimedia data packets start traversing the WiMAX link.

Step 1:

- The WA informs the CSC_MN that the application is started; the required QoS parameters for the application are delivered to the CSC_MN;
- The CSC_MN triggers the NSIS reservation procedure (*NSIS_Reserve_Req*); in this case, the NSIS protocol is used to establish the end-to-end signaling QoS reservation, whereas in the SIP scenarios, the NSIS protocol is only used to establish edge-to-edge QoS signaling;
- The CSC_ASN receives the NSIS signaling and initiates the QoS authorization procedure with the AAA using the Gq' Diameter messages *QAR* and *QAA*.

Step 2:

- Herein the CSC_ASN communicates with the WXLM to perform AC using the *WXLM_QoS_AC.req* message;
- Thereafter, if the WiMAX system is not loaded and the required QoS is guaranteed, the CSC_ASN sends an *WXLM_QoS_Resv.req* message to establish the SF reservation on the WiMAX link;
- The WXLM MIMSs sends the *RR.req* message, which will trigger the *DSA-REQ/RSP* and *C-SFM-REQ/RSP* procedures on the WiMAX link to establish the SF.

Step 3:

- The CSC_ASN triggers the NSIS_Reserve_Req message to perform QoS signaling on both the CSN and the CN;
- The video stream starts flowing from the streaming server towards the MN through the reserved downlink SF.

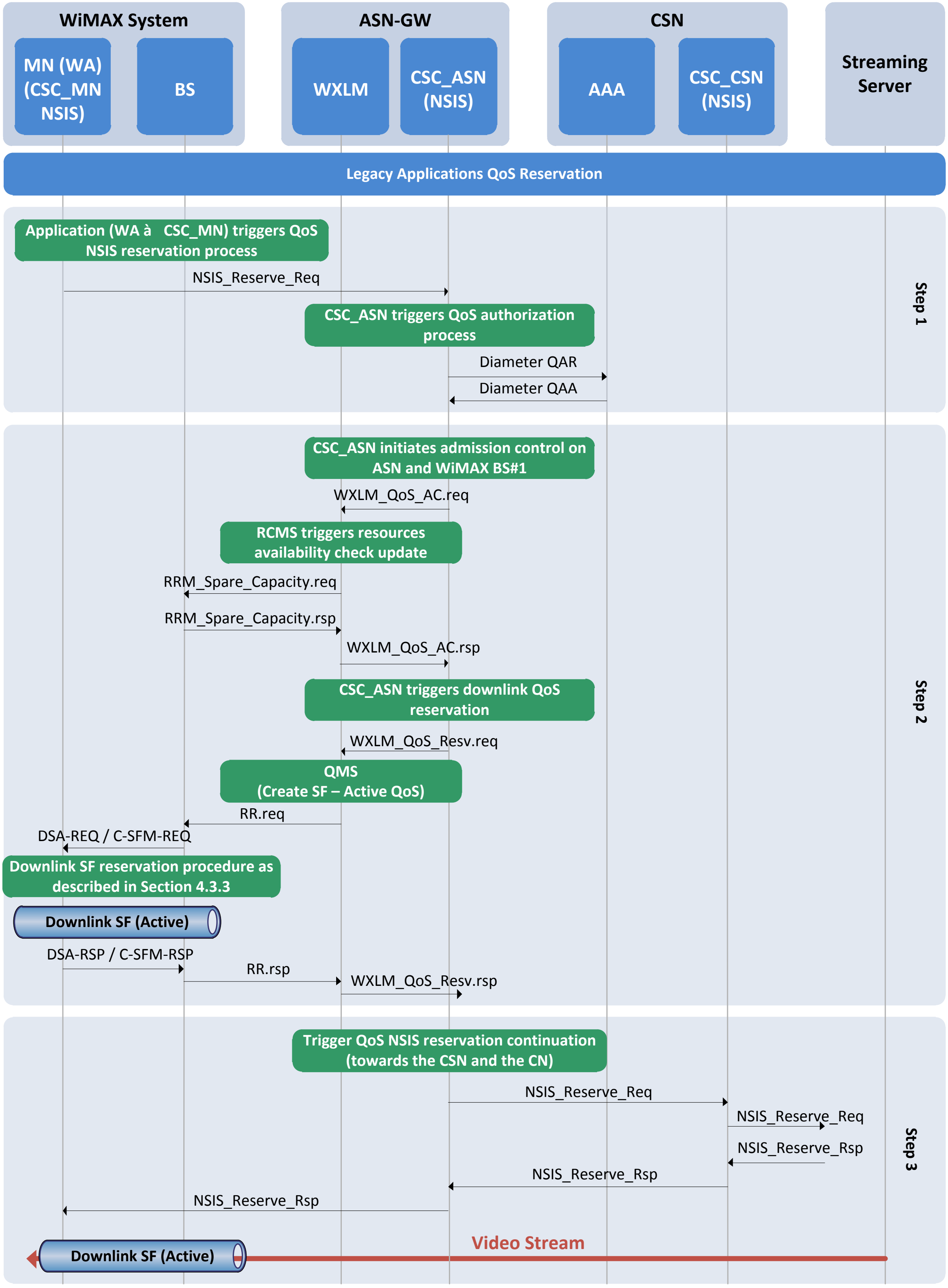

Figure 4-25: WiMAX QoS management for legacy applications

4.5. Experimental Performance Evaluation

This section elaborates on the performance of the WiMAX QoS-enabled architecture described in the previous sections. In section 4.5.1 a set of measurements related to the WXLM are presented, specifically with respect to the QMS. Thereafter, in section 4.5.2, a set of tests that evaluate the QoS performance of the implemented system using VoIP and IPTV services is given [115] [142] [143].

4.5.1. WXLM QoS Signaling Measurements

In order to evaluate the efficiency of the implemented cross layer mechanisms, it is important to integrate the WiMAX system in a NGN environment, which is able to support real time services. Therefore, besides evaluating the performance of the standalone WXLM mechanisms, it is also important to evaluate the global performance of the mechanisms that interact with the WiMAX cross-layer entities. Hence, this section presents an evaluation of the Layer 3 QoS (L3QoS) framework, composed by the CSCs and the NSIS entities, as well as an assessment of the total end-to-end time required to perform a reservation over the WiMAX system.

4.5.1.1. Implemented Demonstrator and Tests Methodology

The demonstrator implemented to validate and evaluate the WiMAX cross layering framework is illustrated in Figure 4-26.

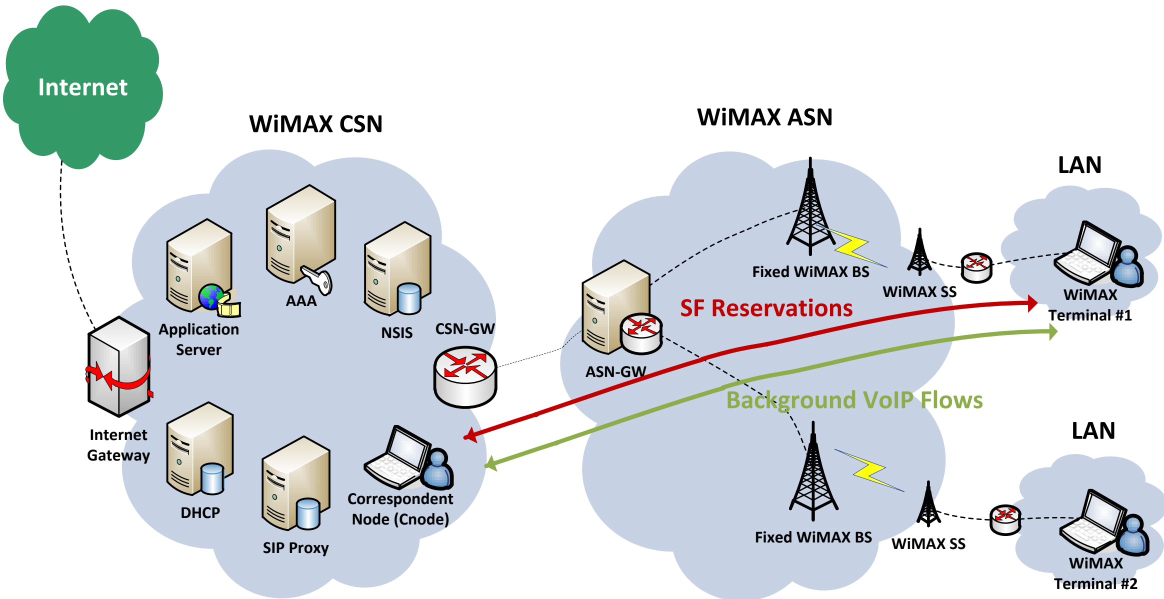

Figure 4-26: Implemented demonstrator for cross-layer signaling measurements

The testbed is composed of three main parts: the CSN, the ASN and the WiMAX Terminal (WT). The ASN is generally composed of several gateways (ASN-GWs), which establish connectivity with the CSN. Moreover, ASN performs relay functions to the CSN in order to establish IP connectivity and AAA mechanisms. A Correspondent Node (CNode) is located on the CSN to establish communication with the WTs. The testbed includes one BS, which provides radio connectivity to the WiMAX SSs in a PtMP topology.

The testbed WiMAX BS operates at 3.5 GHz, with a 3.5 MHz channel using a 64 Quadrature Amplitude Modulation (QAM) scheme with 3/4 Forward Error Correction (FEC). The WiMAX BS is connected to the ASN via the ASN-GW. On the host side, a WT is connected to each WiMAX SS.

Table 4-15: WiMAX testbed parameters

	Description
Base Station	Redline Communications RedMAX AN-100U
Subscriber Stations	Redline Communications Subscriber Unit – Outdoor (SU-O)
PHY	256 Orthogonal Frequency Division Multiplexing (OFDM) Time Division Duplex (TDD)
Frequency Band	3.48 GHz
Channel Bandwidth	3.5 MHz
Downlink Modulation	Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), 16 QAM and 64 QAM
Uplink Modulation	BPSK, QPSK, 16 QAM and 64 QAM
Scheduling Services	BE, rtPS

The Redline Communications certified WiMAX equipment was used since it fully supports the QoS actions that are evaluated: reservations, modifications and/or deletions. The results obtained for every specific QoS action that was evaluated for a specific number of SFs (2, 8, 32, 64, 128 and 256) in both uplink and downlink directions, comprise the mean of three runs.

The processing times were measured with and without background traffic. For the background traffic, a variable number of background VoIP flows (50, 100, 150, 200) was used, as illustrated in Figure 4-26. The VoIP traffic was generated with synthetic traffic load based on the ITU-T G.723.1 codec [168].

4.5.1.2. Results

4.5.1.2.1 WXLM QoS Session Management

The first sets of measurements were devoted to the QoS session's establishments, modifications and deletions. Figure 4-27 illustrates a stacked column graphic, where each column represents a specific module of the ASN-GW (CSC, QMS, MIMS GA and MIMS RCSA).

Each stack column is further split in three parts, each one corresponding to a specific action, namely, QoS session establishment (*blue*), modification (*yellow*) and deletion (*light blue*). For each action, the vertical axis represents the cumulative average time (in milliseconds - ms) to enforce a specific action on the WiMAX system. As an example, the *blue* part of the CSC column represents the cumulative average time, composed by the CSC, QMS, MIMS GA, MIMS RCSA and WiMAX BS modules, to establish the SF reservations in the WiMAX system. The *blue* part of the QMS column describes the QoS reservation cumulative average time, composed by the QMS, MIMS GA, MIMS RCSA and WiMAX BS, whereas the *blue* section of the MIMS GA column provides the cumulative average time, given by the MIMS GA, MIMS RCSA and WiMAX BS modules. Finally, the MIMS RCSA column represents the internal module processing time, as well as the SNMP management messages exchange with the WiMAX BS. On the horizontal axis is represented the number of SFs (2, 8, 32, 64, 128, 256) that have been used for each test. Therefore, each group of four columns represents a specific performance test.

Comparing the obtained results with respect to the type of actions that are being requested to the WiMAX system, the time needed to establish a QoS reservation (*blue*) is approximately 53 % of the total time consumed. The rationale for this behavior is due to the fact that the amount of operations required by the WiMAX system for a QoS reservation is higher compared with the modification and deletion processes. The figure also shows that the most time consuming module is the MIMS RCSA, mainly because it includes the negotiation of the QoS parameters between the BS and the SS through the usage of the DSA/C/D (Dynamic Service Addition / Change / Deletion) messages, as defined in the IEEE 802.16 standard, which is the major time consuming process in the chain. The average time taken by the MIMS RCSA to perform the three actions has a minimum of 17,9 ms for 2 SFs up to a maximum of 20,9 ms for 256 SFs, with small impact on the increase of SFs. The time spent by the remaining modules is due to the message flow and internal processing. The average time measured on the CSC to reserve 256 SFs is 15 ms, 6 ms to modify the previously established SFs and then finally 6 ms to delete the 256 SF reservations at the end of the flow lifetime. In this case, the entire management of the 256 flows required approximately 27 ms.

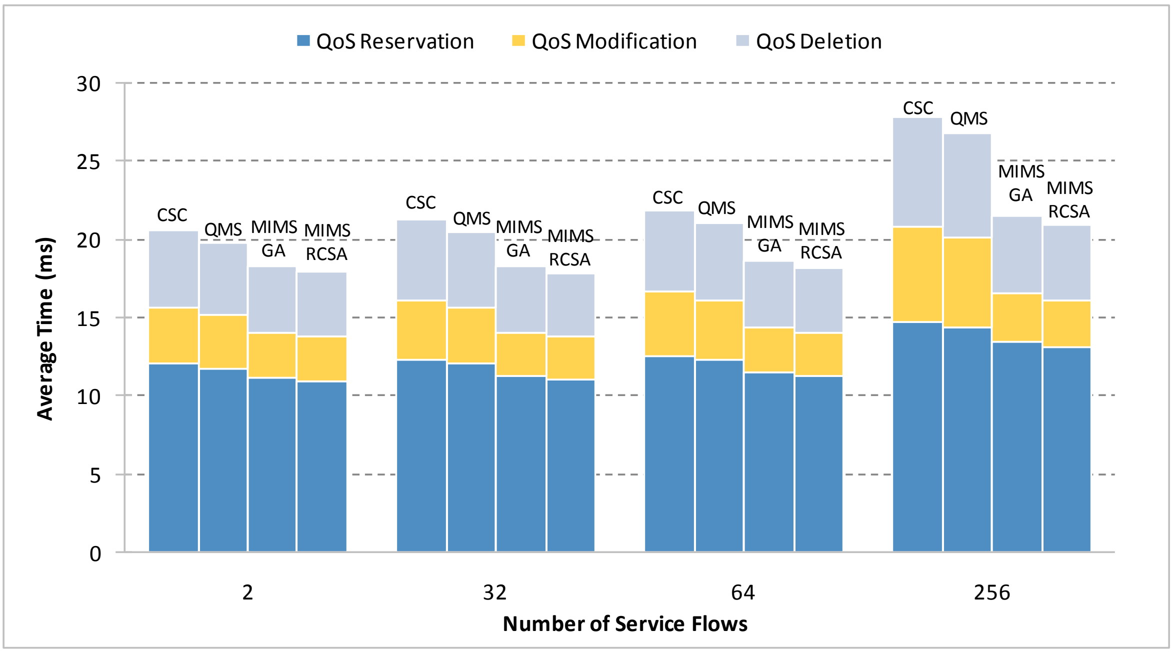

Figure 4-27: QoS reservation, modification and deletion performance measurements

In short, an increasing number of SFs slightly rises the time spent to establish, modify and delete the QoS sessions. This behavior occurs because the number of entries in the hash tables increases, as well as the interaction with the SNMP MIB tables in the WiMAX BS. The overall elapsed time is very good for real-time applications and fast mobility environments, ensuring a desirable quick resource reallocation, from 21 ms for 2 SFs up to 27 ms for 256 SFs.

4.5.1.2.2 MIMS QoS Session Management

Next, a discussion and analysis of the MIMS RCSA performance results is provided. A considerable array of times was collected in order to analyze the time distribution along the different tasks accomplished by MIMS RCSA. The RCSA, as described on section 4.3.5.1, is the module that interacts with the WiMAX equipment. Thus, the total time spent from the reception of a request (SF reservation, SF modification and SF deletion) to the sending of the correspondent answer to the MIMS GA was obtained; the partial times were also gathered, in order to distinguish between the internal processing time of the RCSA module and the time it takes to set each SNMP MIB table. Figure 4-28 illustrates the RCSA performance times. The *RCSA Reservation, Modification and Deletion Total Path* blocks show the total time used by RCSA to process each request, that is, the entire path since it receives a request from the MIMS GA, until it sends back the response to the latter. The *MIMS RCSA Reservation, Modification and Deletion Total SNMP Set* blocks represent the sum of all *SNMP Set* times needed, respectively, for a SF reservation, modification, or deletion. Finally, the *RCSA Reservation, Modification and Deletion Internal Processing* blocks represent the internal processing time of RCSA routines.

As can be observed in Figure 4-28, the RCSA internal processing time is so small that the total path time is almost not affected, and therefore unseen on the graphic bars. In the worst case, the internal processing time is less than 55 us. This case occurs when 256 SFs are deleted, which causes the module to deal with considerable processing work when looking for the associated indexes to set the SNMP MIB tables.

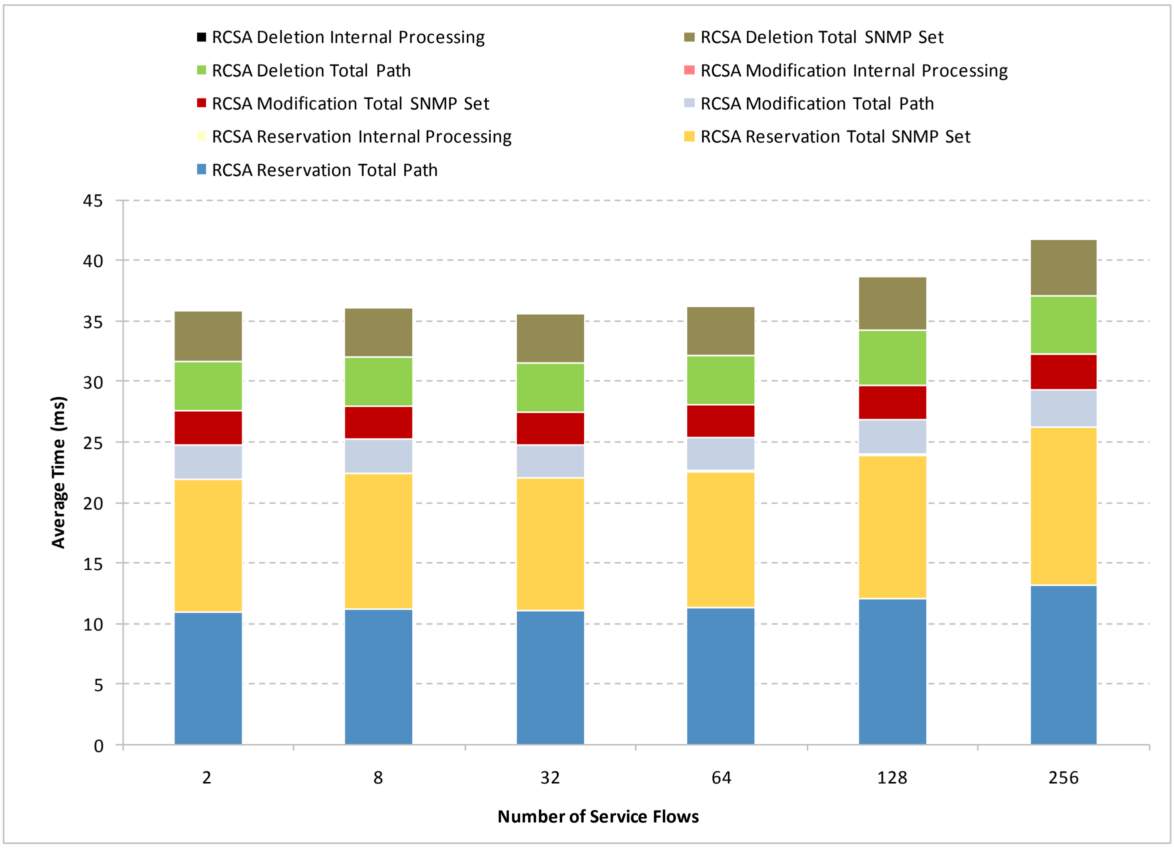

Figure 4-28: MIMS RCSA performance

Another important fact that can be concluded from the graphic is that QoS session's establishment takes more time than the deletion ones, and these, in turn, are more time consuming than the modification requests. Furthermore, it is also possible to perceive that there is a slight increase of time when the number of SFs increases. Nevertheless, these values are kept stable, showing that the RCSA and the WiMAX equipment are prepared to deal efficiently with a large number of sequential requests. Finally, the differences between the *RCSA Reservation, Modification and Deletion Total SNMP Set* processing times are due to the different amount of Object IDs (OIDs) that have to be set on the WiMAX MIB, which is larger for the reservation requests when compared to modifications or deletion ones.

Table 4-16 details all the SNMP MIB Tables, and the correspondent OIDs number that are assigned when performing a SF reservation, modification and deletion.

Table 4-16: WiMAX QoS MIB tables

MIB Tables	Functionality	OIDs
DEL: ServiceClassTable	Contains the SF QoS parameters	1
MOD: ServiceClassTable		5
RESV: ServiceClassTable		12
DEL: ProvisionedSfTable	Contains the SF profiles provisioned by the NMS	1
RESV: Provisioned SfTable		5
RESV: ProvisionedForSfTable	Maps the MAC addresses of SSs to the provisioned SFs	1
RESV: ClassifierRuleTable	Contains packet classifier rules associated with SFs	14

Figure 4-29 shows the time spent by every single SNMP MIB table set. Once again, the inherent processing time is coupled with the increased number of SFs requests, staying a little higher as the number of sequential requests increases. Furthermore, the time taken to process each *SNMP Set* is also strictly related with the number of OIDs that must be set in each operation – the greater the number of OIDs to assign, more time is spent on performing this task by the equipment. The differences that occur when setting distinct SNMP MIB tables with the same OIDs number are due to the inherent processing time of WiMAX equipment for those tasks. For instance, erasing an existing SF by the WiMAX equipment is more time consuming than just doing some amendment to the QoS parameters of an existing one. Moreover, when deleting a *ProvisionedSfTable* row entry, at the same time, all the associated entries in *ProvisionedForSfTable* and *ClassifierRuleTable* are also being deleted. For that reason the deletion process when erasing elements of *ServiceClassTable* is smaller than when deleting elements from *ProvisionedSfTable*.

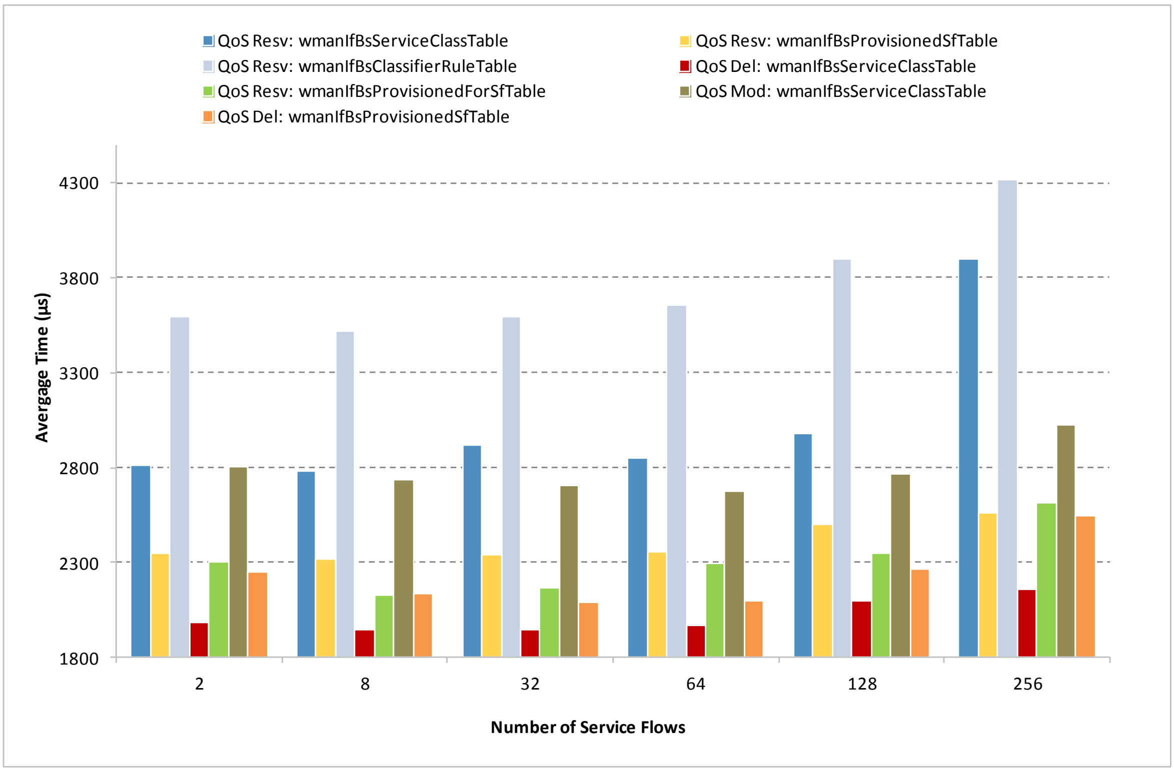

Figure 4-29: Single *SNMP Set* performance

4.5.1.2.3 WXLM QoS Reservation with Background Traffic

Figure 4-30 presents the processing time that the WXLM system, namely CSC, QMS, MIMS GA and WiMAX BS modules, need to establish a QoS reservation. After the NSIS reservation message arrives at the ASN-GW, the CSC_ASN will enforce the QoS reservation in the WiMAX segment.

Figure 4-30 shows that the WXLM system processing time depends on the number of VoIP flows that are traversing the WiMAX link. Basically, this time includes the modules processing time, the SNMP management messages exchange with the WiMAX BS, and the DSA MAC management messages, which represent the major time consuming process in the chain.

Without background VoIP flows, the average time in the WXLM system modules is very small (approximately 11.5 ms) and the results of the tests are similar. When there are 50 and 100 VoIP background flows, the average time is approximately the same, on median, but with a higher variability. In the tests with 150 and 200 VoIP flows, the median measured time increases slightly, to 12 ms and 13 ms, respectively. Note that the processing time is always less than 15 ms in all tested configurations.

In short, an increasing number of VoIP background flows slightly rise the time spent to establish and activate a QoS reservation in the WiMAX link. This is expected, as the QoS signaling traffic is not differentiated from the background VoIP traffic, and the request processing time increases due to larger number of entries in the hash tables and the interaction with the SNMP MIB tables in the WiMAX BS. Nevertheless, the overall processing time does not introduce a significant overhead, which is well suited for real-time applications and fast mobility environments, ensuring a fast resource reallocation, ranging from 11 ms without background VoIP flows up to 13 ms for 200 VoIP background flows. Therefore, the testbed results indicate that the impact of the WiMAX cross layer system in establishing a QoS reservation is rather small and within acceptable bounds.

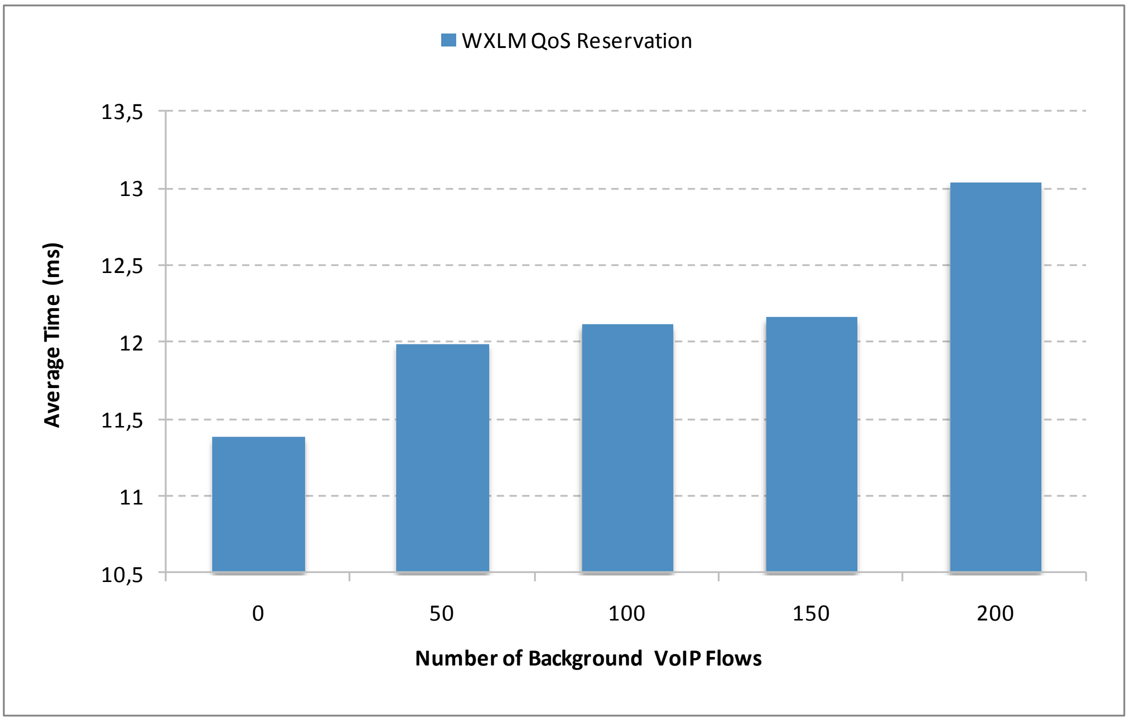

Figure 4-30: WXLM system modules processing time vs. number of background VoIP flows

4.5.1.2.4 Layer 3 QoS Management

Figure 4-31 apportions the processing delays to each of the individual L3QoS modules. Each stack column is split in three parts, each one corresponding to a specific segment of the L3QoS communication in the end-to-end path, namely, between the MN and the ASN (*blue*), the ASN and the CSN (*yellow*), and finally between the CSN and the MS (*light blue*). For each column segment, the vertical axis represents the cumulative average time (in ms) to successfully perform L3QoS request processing and communication between the different entities, whereas the horizontal axis represents the number of background VoIP flows that are traversing the WiMAX link, when the QoS reservation is made.

Without background traffic, the L3QoS performance between the MN and the ASN (including the WiMAX segment) takes an average time of 950 ms. When 50 background VoIP flows are injected into the WiMAX link, the average processing time remains the same. When 100 and 150 background VoIP flows are introduced, the average time increases to almost 2 s, and it reaches almost 3 s when 200 VoIP flows are transported over the WiMAX link. Analyzing the results between the MN and the ASN, it results that, due to the VoIP traffic increase, the WiMAX link saturates, and therefore, the L3QoS processing and communication time increases significantly.

With respect to the L3QoS behavior between the CSN and the MS, the processing time also increases when the VoIP background traffic in the WiMAX channel increases. The L3QoS communication between ASN and CSN remains constant across the different experiment configurations, and is only a small fraction of the total time (approximately 100 ms).

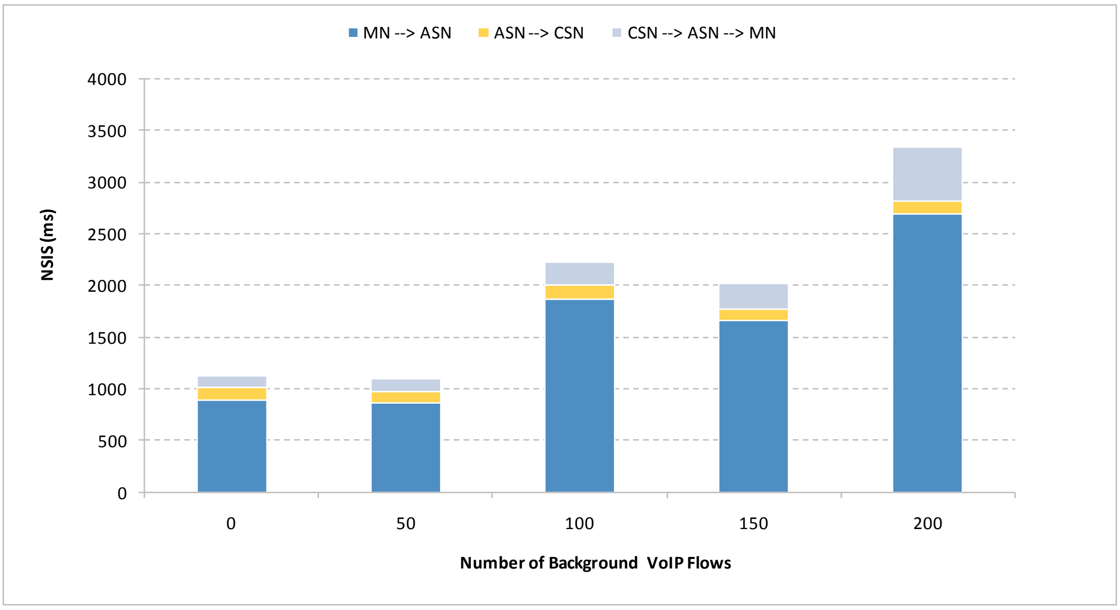

Figure 4-31: L3 QoS performance time vs. number of background VoIP flows

4.5.1.2.5 E2E QoS Session Reservation

Finally, Figure 4-32 presents the time needed to establish an end-to-end QoS reservation. The vertical axis represents the total time needed to perform the QoS reservation; the horizontal axis depicts the number of background VoIP flows traversing the WiMAX link.

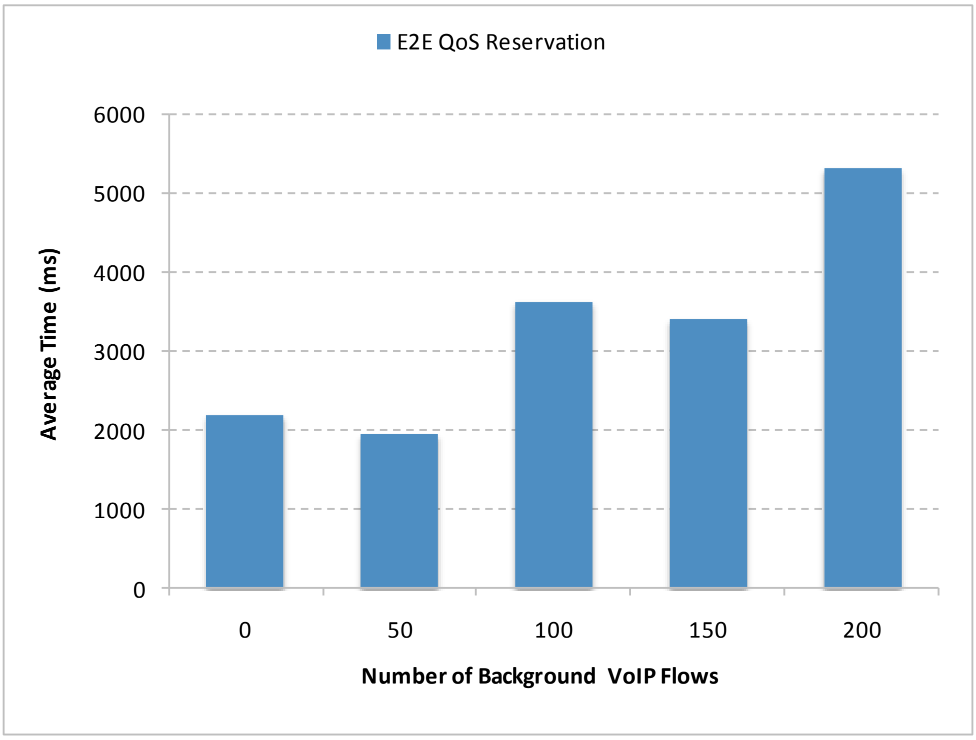

Figure 4-32: End-to-end processing time vs. number of background VoIP flows

It is possible to see that the end-to-end time for reservation establishment depends on the number of VoIP flows that are traversing the WiMAX link. The median end-to-end time is approximately 2 s without background VoIP flows and 5 s for 200 VoIP flows. It is also visible a peak at approximately 7 s when 200 background flows are introduced. These results are mainly due to the L3QoS performance. Another significant component of the end-to-end processing delay is the time consumed by the Diameter protocol communication between the CSC_ASN and the AAA, which is approximately 1 s, independently of the presence of any VoIP background flows.

4.5.2. WXLM QoS Measurements

It is widely anticipated that the next generation wireless networks will handle an exponential growth of audio/visual content. In order to evaluate the QoS performance over WiMAX, it is important to test the WiMAX system with real time services, such as VoIP and IPTV. Hence, this section presents an evaluation of the WiMAX performance using VoIP and video streaming services.

4.5.2.1. Implemented Demonstrator and Tests Methodology

The demonstrator implemented to validate and evaluate the WiMAX QoS performance is illustrated in Figure 4-33. An approach similar to the one presented in [169] [170] [171] [172] is followed, with multiple competing traffic sources over a PtMP WiMAX topology, and the capacity of the WiMAX link to handle a multitude of VoIP flows between the SSs is measured, while simultaneously delivering a variable number of IPTV streams. As depicted in Figure 4-33, an IPTV service is emulated, running between the CNode and WT1 (connected to SS1), in parallel with QoS and BE VoIP conversations, both running between WT1 and WT2. By gradually increasing the number of IPTV streams, the saturation point of the WiMAX downlink channel is determined. Each run is repeated ten times, with a fixed duration of 60 seconds, and measured the application throughput, packet loss and delay.

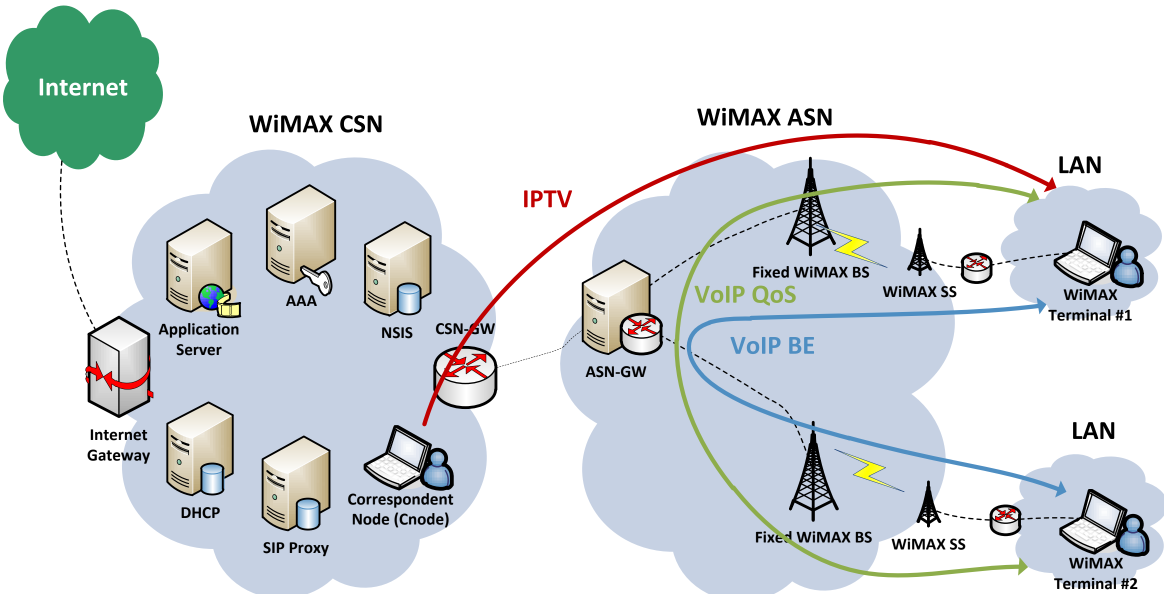

Figure 4-33: Implemented demonstrator to evaluate QoS performance

To study the behavior of the WiMAX system using different SCs, different SFs for each service were used, as described in Table 4-17. The rtPS SC was employed for both VoIP QoS and IPTV traffic, giving lower priority to the IPTV traffic. For VoIP QoS traffic, four SFs were created, two per SS (one for uplink and one for downlink), whereas for IPTV traffic, a downlink SF on SS1 domain has been created. The VoIP BE traffic between SS1 and SS2 is emulated in a similar way to the VoIP QoS traffic, but using the BE service class, in order to differentiate both VoIP services.

Before proceeding with the evaluation, the maximum throughput that can be obtained in the WiMAX system is measured. The WiMAX link is saturated and measured the maximum application-level throughput, also called throughput, on the downlink and uplink directions. The test was made with different Maximum Transmission Units (MTU), and obtained the best results for application payloads of

1472 bytes (MTU = 1500 bytes, the recommended MTU size for IEEE 802.16 standard-compliant equipment). For the uplink, the average maximum measured throughput was 4.75 Mbps and for the downlink it was 5.75 Mbps, with negligible (<0.1%) packet loss.

Table 4-17: Services involved in the QoS evaluation

Service	Service Class	Service Flow	Direction
VoIP QoS (1)	rtPS	SS1 → BS; BS → SS2	WT1 → WT2
VoIP QoS (2)	rtPS	SS2 → BS; BS → SS1	WT2 → WT1
VoIP BE (1)	BE	SS1 → BS; BS → SS2	WT1 → WT2
VoIP BE (2)	BE	SS2 → BS; BS → SS1	WT2 → WT1
IPTV	rtPS	BS → SS1	CN → WT2

In order to emulate a set of IPTV streams, twenty minutes of live IPTV unicast transmission were used and a packet trace created. The captured video stream was in H.264 – Motion Picture Experts Group (MPEG-4) format, or Advanced Video Coding (AVC), also known as MPEG-4 Part 10 [173] and the accompanying audio stream was encoded in MPEG-1 Audio Layer II, also known as MP2 [174]. The content of the transmission was a music video TV channel configured with video stream at 512 Kbps (360×288, 25 f/s), and the audio at 192 Kbps, emphasizing audio over video quality. The captured video stream has a Variable Bit Rate (VBR). The total packet sizes of the video varied greatly, with the biggest value being at 1492 bytes. It was also emulated the corresponding IPTV audio stream using Constant Bit Rate (CBR) traffic with the total packet size fixed at 634 bytes (including codec payload and RTP/UDP/IP/MAC headers). The video and audio parts of the IPTV traffic are separated and streamed to different ports. Using the obtained packet trace, it was possible to create trace files with all packet sizes and inter-arrival times for video and audio. Based on these trace files, N IPTV A/V streams were started from a random point in the twenty minute long IPTV packet trace. JTG [175] was used to generate the trace-driven IPTV streaming traffic. The source of the N A/V streams is located at the CNode while the sink is the WT1 connected to SS1.

In addition to the N A/V streams, C bidirectional VoIP flows are injected using JTG with source/sink pairs in the domains of SS1 and SS2. Speex [176], an open source audio codec specially designed for VoIP applications over packet switching networks, was used. Speex is designed to be robust against packet loss and has been incorporated in several applications. C Speex VoIP flows were emulated each with a wideband codec bitrate of 12.8 Kbps using JTG. For each VoIP flow, JTG generates 50 packets/s with 32 bytes of codec payload, thus leading to an effective application bit-rate of 17.6 Kbps (including RTP headers). After adding a total of 28 bytes of UDP and IP headers, each JTG instance injects 28.8 Kbps of total emulated Speex CBR traffic into the network. In order to test VoIP backhauling inside the same WiMAX cell, C = 50 simultaneous, bidirectional flows were introduced, yielding an application throughput (Speex payload plus RTP header) of 880 Kbps. This is only 18.5% of the maximum uplink throughput of 4.75 Mbps, measured with MTU sized UDP packets.

For high-precision one-way delay measurements, accurate clock synchronization is necessary, taking care of both absolute time and clock drift at different hosts in the network. For the one-way delay measurements, both absolute time and clock drift are important. The IEEE 1588 Precision Time Protocol (PTP) open source server [177] was used to synchronize the clocks of all hosts. Although PTP injects a very small amount of traffic when compared with the rest of the sources in our tests, it is preferable that PTP signaling does not interfere with the measured traffic, and therefore the testbed synchronization was made using a different network. After initializing PTP in each machine and waiting the necessary time for achieving synchronization, the offset between the different host clocks was lower than 100 µs.

4.5.2.2. Results

4.5.2.2.1 Packet Loss

Herein it is presented the measured packet loss for VoIP (with and without QoS) and for IPTV, as illustrated in Figure 4-34. Accordingly with the results at SS1 for audio and video, the BS – SS1 WiMAX downlink can handle N <= 3 simultaneous A/V streams in parallel with the VoIP traffic with negligible packet loss, as for tests with BE. When N >= 4, packet loss for IPTV increases rapidly, which is unacceptable. The packet loss values for video and audio are higher than in the tests performed only with BE. In this case, the priority for IPTV traffic (both audio and video) is lower than for VoIP (with QoS) traffic, and then IPTV traffic has to wait for the WiMAX channel to be free. It causes the increase of packet loss because the queue in the WiMAX segment, for IPTV traffic, will saturate earlier than in the previous situation. For VoIP (with QoS) the results are as expected because this is the most priority traffic with lower packet loss. However, the BE traffic (VoIP without QoS) presents a high level of packet loss, as we expected, since it has the lower priority value amongst all others. Note that with 5 IPTV streams, it keeps almost 100% of packet loss. As expected, this demonstrates that good quality in BE is only possible when the link is not saturated.

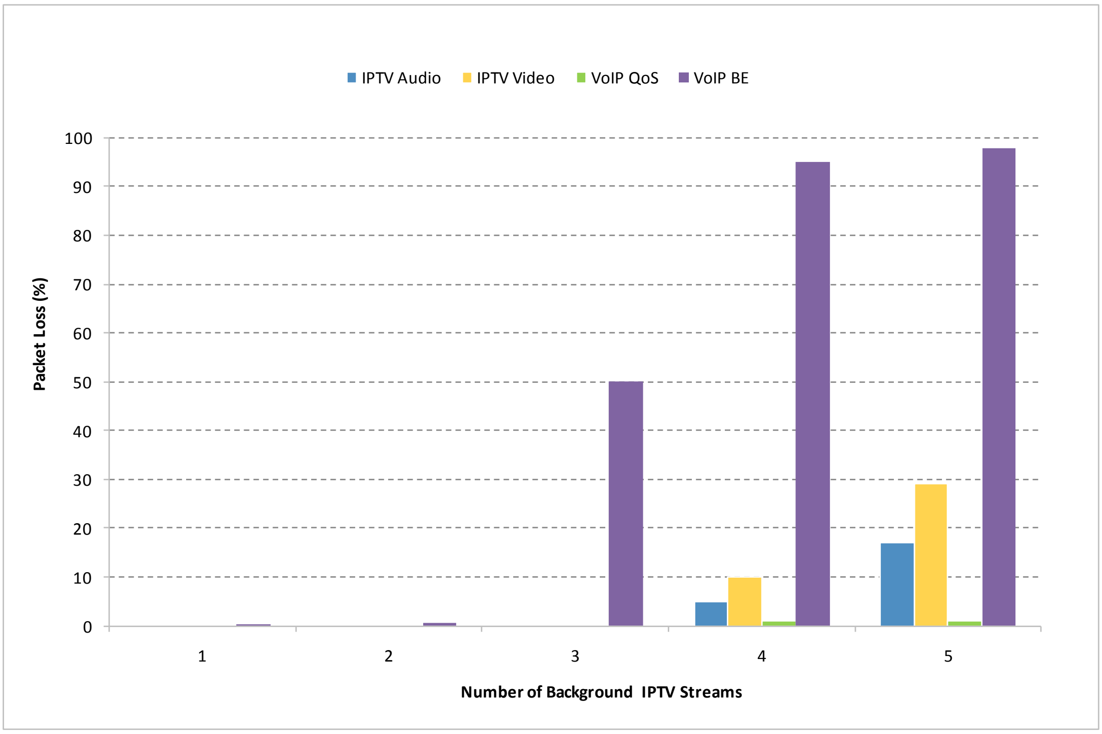

Figure 4-34: Measured packet loss vs. number of IPTV streams

4.5.2.2.2 Packet Throughput

The application throughput results, depicted in in Figure 4-35 and Figure 4-36, provide the same conclusions than the packet loss results. In result of the higher service class for VoIP (with QoS), this traffic always has the bandwidth of WiMAX segment that it needs, whatever the number of IPTV streams. When N >= 4, throughput for IPTV decreases rapidly, which is unacceptable. This is again reflecting the lower priority of IPTV traffic compared to the VoIP (with QoS) one. The BE traffic has no bandwidth available when the WiMAX link starts to saturate because of its lower priority.

Since the VoIP QoS traffic has higher priority than the IPTV and VoIP BE traffic, it will be able to use the amount of bandwidth needed, independently of the number of IPTV streams that are traversing the WiMAX link. When the WiMAX link starts to saturate, there is no bandwidth available for the VoIP BE traffic due its lower class of service.

Finally, with respect to the packet delay, when N >= 4, the one-way delay for IPTV increases faster compared with the results with BE. In this case the priority for IPTV traffic is lower than for VoIP (with QoS) traffic. Therefore, the IPTV traffic has to wait for the WiMAX channel to be free. For VoIP (with QoS) the results were expected because this is the most priority traffic. The delay is associated with the WiMAX equipment used because it is usually the delay involved in a WiMAX link. The BE (VoIP without QoS) traffic has to wait more time to be serviced when the WiMAX link starts to saturate because it has a lower priority.

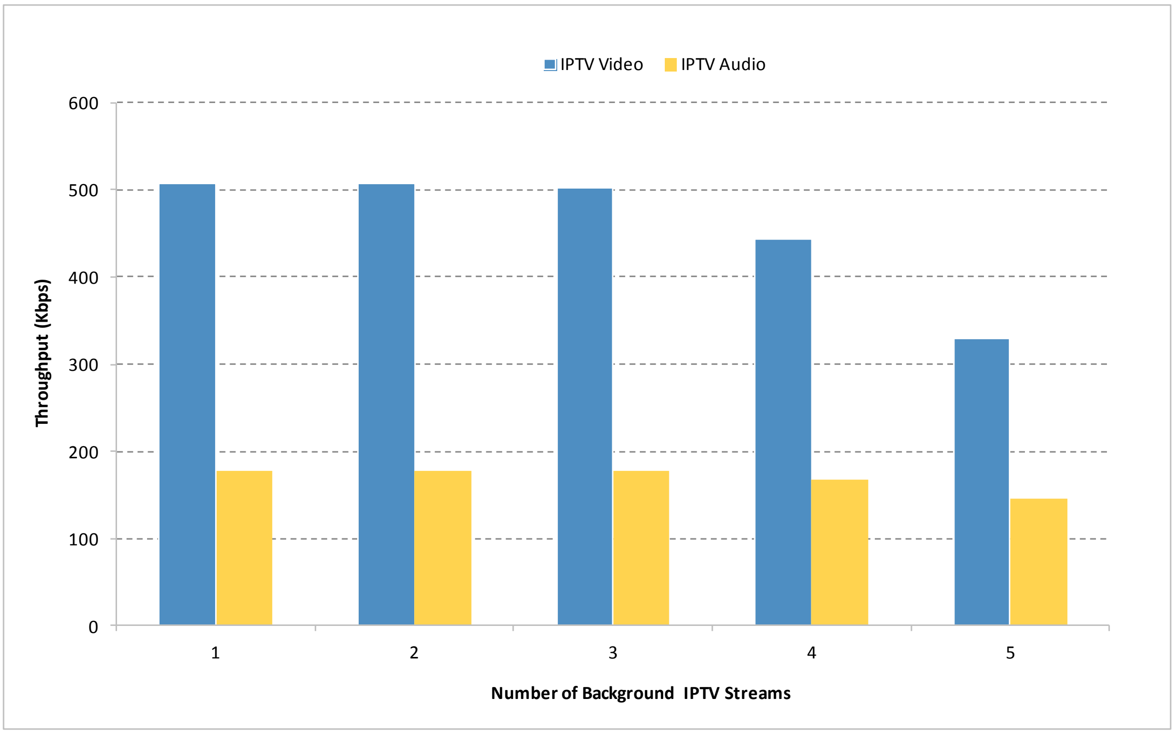

Figure 4-35: Measured video throughput vs. number of IPTV streams

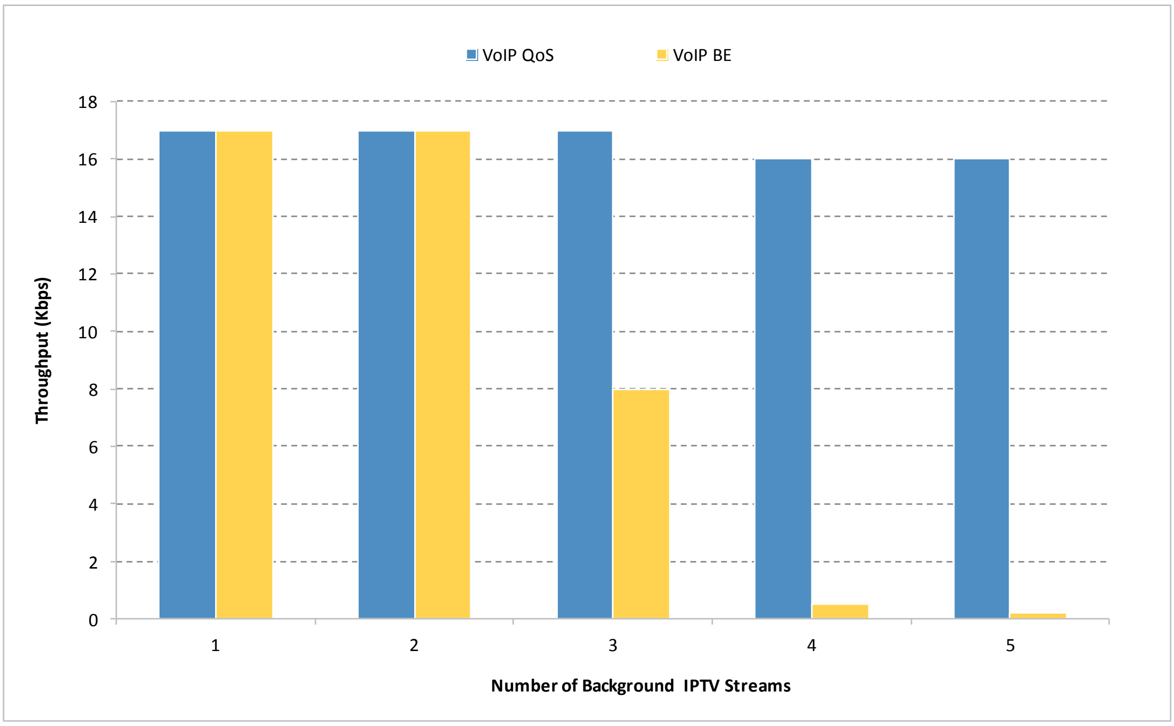

Figure 4-36: Measured VoIP throughput vs. number of IPTV streams

4.5.2.2.3 One-way Delay

The one-way delay results are illustrated in Figure 4-37 and Figure 4-38. When N >= 4, the delay increases faster for IPTV compared with the results with BE. In this case the priority for IPTV traffic is lower than for VoIP (with QoS) traffic. Therefore, the IPTV traffic has to wait for the WiMAX channel to be free.

For VoIP (with QoS) the results were expected because this is the most priority traffic. Since the BE (VoIP without QoS) traffic has a lower priority, it has to wait more time to be served when the WiMAX link saturates.

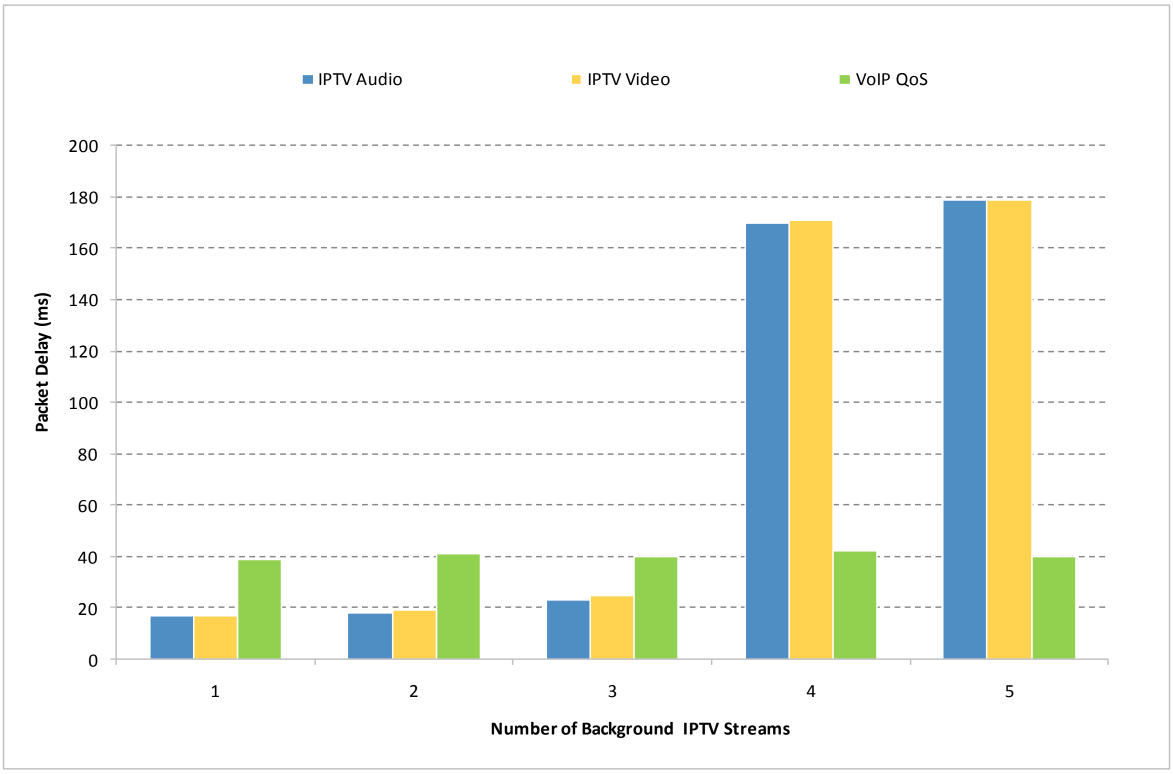

Figure 4-37: Measured one-way delay for QoS traffic vs. number of IPTV streams

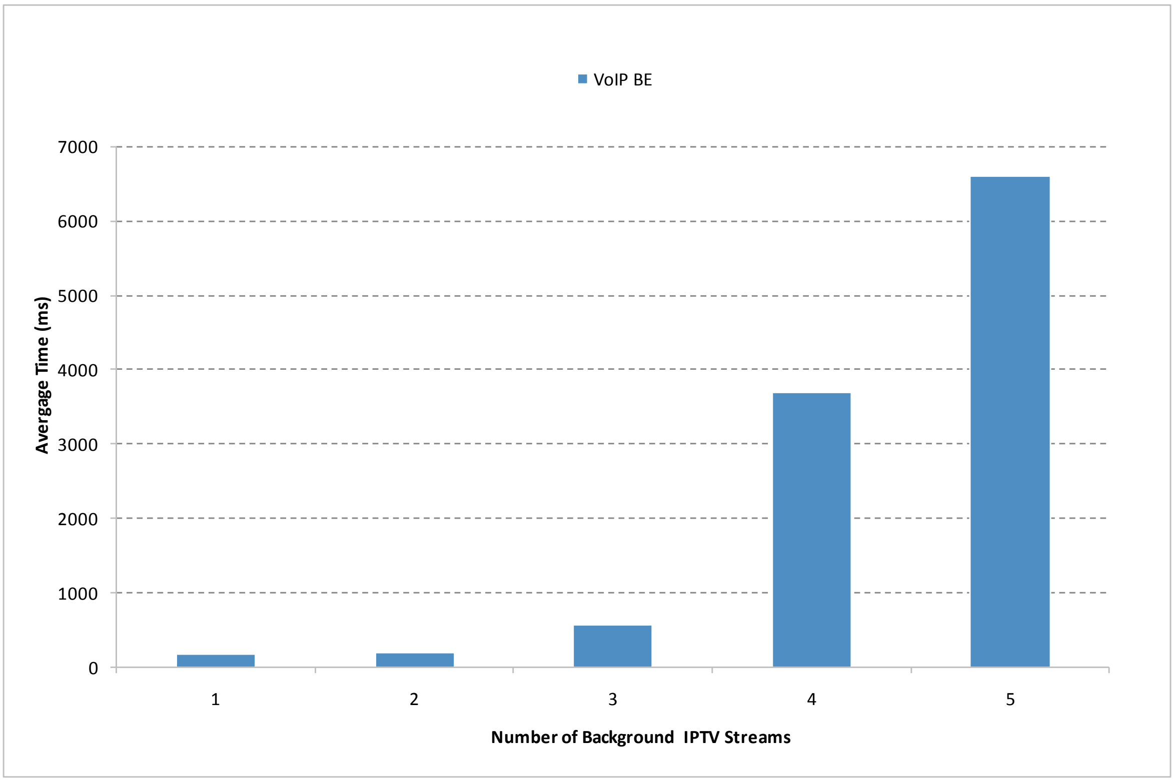

Figure 4-38: Measured one-way delay for BE traffic vs. number of IPTV streams

4.6. Summary

Using WiMAX as a next generation access technology, both for fixed and mobile connectivity, is a promising technology for a large number of real application scenarios in the academic, scientific and research community. The analysis of the new applications requirements highlighted the necessity to smoothly integrate, from the beginning, the WiMAX technology into the NGN architecture in order to incorporate the existing features and to be compliant with the infrastructure that will be present in the market in the near future.

This chapter described a solution for a complete WiMAX end-to-end network environment, by defining and specifying a complete and open system architecture to fulfill the new applications requirements in terms of QoS. The main focus of the designed architecture is related with QoS provisioning comprising resource management, resource request signaling and reservation as well as resource control, for which detailed architectural design is presented. The architecture definition has been followed by system design and prototype implementation. The system accommodates several types of applications. When the applications are not IMS compliant, as the case of some of the scenarios described, some enhancements at client and network side will permit the communication of the user requirements in terms of QoS introducing new functional modules such as the WA, the NSIS signaling modules and cross-layer management system.

In this context the proposed architectural solution exhibits adequate flexibility by supporting a complete range of applications with respect to signaling. In detail these applications are:

- SIP applications: direct interaction between SIP Proxy and ASN-GW;
- Open-source applications: a particular API (WLAI) is provided in order to interface with the QoS signaling framework;
- Closed-source applications: the WA is used as a translator between the applications and the QoS control plane.

To provide several services in the network (such as mobility, QoS, network management, AAA and multicast/broadcast services) independently from the equipment specific functionalities, between the WiMAX technology and the higher layer entities of the designed architecture, a WiMAX cross-layer manager was specified and implemented. The WXLM provides independency between the network control plane and the WiMAX system through standardized interfaces. The presented system architecture, developed as a practical use case in the WEIRD project, comprised, integrated in the WXLM, among others, a QMS for the support of QoS reservations, modifications and deletions.

For the selected scenario it was also shown that the end-to-end QoS signaling and resources reservation interaction performed according to the planned design and revealed acceptable performance figures. Special attention was given to the WXLM system, which provides a set of WiMAX services and independency between the network control plane and the WiMAX system. With respect to the signaling results, the cross layer processing times, as measured in our WiMAX testbed with a prototype implementation, are on median in the range of 12 ms and always less than 15 ms, even for 200 VoIP background flows simultaneously injected in the WiMAX link. On the other hand, the end-to-end reservation processing times are significant, due to the NSIS framework, the CSCs and the Diameter protocol processing. In terms of the level of QoS achieved, the proposed architecture is able to support the differentiated services requirements. The experimental results from our prototype implementation indicate that the proposed cross-layer architecture can be efficient and compliant with real time services and next generation environments.

In the following chapter the presented WiMAX QoS-enabled architecture is extended with seamless mobility functionalities.

5. Integrated Mobility and QoS Control for WiMAX Access Networks

WiMAX is a wireless digital communication system, also known as IEEE 802.16, intended for Wireless Metropolitan Area Networks (WMAN). One of the central concerns in the emerging telecommunications environment is the support for seamless mobility. There are several proposals for fast and seamless mobility management between different Access Networks (ANs). Moreover, the integration of multiple wired and wireless technologies is being studied by IEEE under the IEEE 802.21 umbrella, also known as Media Independent Handover (MIH) [39]. Seamless mobility requires the active support of Quality of Service (QoS) related mechanisms in the handover process, guaranteeing that resources are reserved in the Target AN (TAN) before mobility management operations are completed. Therefore, it is clear that mobility management cannot be dissociated from QoS processes.

This chapter describes and presents an evaluation of a WiMAX compliant architecture based on IEEE 802.21, which integrates mobility and QoS mechanisms. The proposed architecture, developed in the scope of the European research project WEIRD [139] [140], enhances the mobility mechanisms in WiMAX ANs and is appropriate for NGN environments [27] [154] [155] [178]. The architecture integrates QoS functionalities, specifying mechanisms to enable the complete combination of mobility and QoS, using an extension of the Next Steps in Signaling (NSIS) framework with 802.21 information [179].

In order to fully integrate horizontal mobility procedures with the previously defined WiMAX QoS-enabled architecture, the WXLM was extended with the IEEE 802.21 services under the scope of this Thesis. Thus, the WXLM is able to establish the required bidirectional cross-layer mobility communication, that is, to support the exchange of IEEE 802.21 commands and events between the WiMAX system and the mobility management and control entities of the upper layers. Furthermore, for the successful integration of the IEEE 802.21 platform with WiMAX, it was proposed the translation and mapping of the IEEE 802.21 primitives with WiMAX, more specifically with IEEE 802.16g [41]. As a result, it was required to set new primitives for both standards. Another proposal made under the scope of this Thesis, together with University of Coimbra [182], Nextworks [183] and University of Groningen [184], is related with the transport of 802.21 protocol messages using NSIS, which is already used to transport QoS signaling and meets the transport mechanism requirements of IEEE 802.21.

Herein is also presented the final and overall results of the advanced WiMAX mobility scenario using a real demonstrator. The data results show that the one way delay for the different applications is approximately the same for all, around 10 ms, while the applications' throughput is always close to the theoretical values. In terms of the control plane results, the architecture modules introducing higher delay correspond to the NSIS modules, as the association mechanisms of General Internet Signaling Transport (GIST) have a high influence on the background traffic [180]. Although most of the signaling control timings are approximately constant with the increase in the network load, they increase sharply when the network gets congested (120 users in the tested scenario). Overall, the handover effect in the application flows is not noticeable, as all the process is prepared beforehand, and QoS is established in the new WiMAX network [181].

This chapter is organized as follows: section 5.1 provides an overview of the designed QoS and mobility architecture for WiMAX; section 5.2 describes the required mobility services for the WXLM presented in chapter 4, namely the Media Independent Handover management Service (MIHS) and the Mobility Management Service (MMS); section 5.3 explains the usage of NSIS as the transport protocol for the MIH primitives; section 5.4 presents a set of message sequence charts to illustrate the WXLM operation in a macro-mobility scenario; section 5.5 introduces the experimental scenario for the mobility-related performance measurements; finally, section 5.6 details a set of performance results obtained for the WiMAX QoS and mobility enabled framework, whereas section 5.7 summarizes the chapter.

5.1. WiMAX QoS and Mobility Architecture

This section describes the mobility extensions to the WiMAX QoS-enabled architecture described in the previous chapter. A brief overview of the main design guidelines, as well of the modules and protocols involved in the mobility architecture definition are provided in section 5.1.1 and in section 5.1.2, respectively.

5.1.1. Architecture Design Guidelines

The main objective of this chapter is to extend the QoS-enabled architecture presented in the previous chapter with seamless mobility functionalities in WiMAX access environments. Seamless mobility, also known as *make-before-break* handovers, requires service continuity, meaning that, from the user perspective, the handover process must not have a negative impact on the services that are running on the mobile terminal. In order to have a *make-before-break* handover approach, it is mandatory to integrate the QoS mechanisms within the mobility procedures. This integration is very important during the preparation phase of the handover, in which the target network resources have to be allocated taking into account the QoS parameters required for the application, or applications, that will be handed over to the selected target network. Besides the QoS integration, another fundamental aspect to achieve a handover without packet loss and minimum delay is to detect the exact moment when the WiMAX radio link conditions decrease below a minimum threshold and therefore the handover procedures should start. If the handover detection point is not accurate, all the handover process is compromised.

The designed extensions for mobility are based on cross-layer mechanisms, providing the link layer information to the upper layer decision entities, either QoS or mobility related, to activate the correspondent procedures at the most appropriated moment. This is achieved by extending the WiMAX Cross-Layer Manager (WXLM) system described in the previous chapter with mobility services at the terminal and at the network side, enabling both mobile and network initiated handovers, respectively.

Likewise the depicted WiMAX QoS-enabled architecture, the developed mobility service extensions follow the guidelines defined by the WiMAX Forum, involving all the entities defined in the Network Reference Model (NRM), namely the Mobile Node (MN), Access Service Network (ASN) and Connectivity Service Network (CSN). Furthermore, open standards were used for the mobility architecture extensions, such as NSIS for end-to-end resource reservation, MIP for mobility management and IEEE 802.21 Media Independent Handover (MIH) [39] for optimizing the mobility procedures and providing the mobility manager with link layer triggers.

QoS and mobility are managed in a coordinated way at the control plane level through the inter-communication and the combined processing of the Connectivity Service Controller (CSC) modules, located in each segment of the NRM, and their interaction with the WXLM and the application layer. It is important to highlight that QoS and mobility management are strictly correlated and interdependent in WiMAX networks. QoS in WiMAX links is supported by a connection-oriented approach. Each WiMAX connection is associated with a set of downlink or uplink Service Flows (SFs) characterized by a specific profile that defines both the scheduling class and the QoS parameters (bandwidth, priority, latency, jitter). Within the defined architecture, each application session is associated with a set of end-to-end SFs with a QoS description based on the traffic type and application requirements.

With respect to mobility, the user must be able to move between different ANs. The mobility management architecture must be able to support handovers between WiMAX Base Stations (BS), located in the same ASN or in different ASNs, but must also be prepared to support handover between different access technologies, like Wi-Fi and 3GPP networks (as presented in chapter 6). Furthermore, handovers might be initiated and controlled by the network, also known as Network Initiated Handovers (NIHO), or by the terminal, called Mobile Initiated Handovers (MIHO). All these types of handovers must be transparent for the user and the same QoS level must be maintained during the entire length of the sessions, also assuring Authentication, Authorization and Accounting (AAA) services seamlessly and end-to-end QoS: resources must be reconfigured at the control plane level according to the QoS requirements of the active sessions involved in the handover, if this handover is authorized through the user contracts. Therefore QoS and mobility need to be managed together through an interaction between the control plane and the WiMAX lower layers.

Notifications about the current link status can be processed by the mobility manager modules at the MN and ASN, in order to manage handovers through procedures that are completely transparent for the application layer. In particular, handover management in WiMAX networks involves the automatic reconfiguration of the wireless links through a make-before-break approach: the “make” phase includes the creation and the activation of new SFs in the segment between target Subscriber Station (SS)/Mobile Node (MN) and target BS, and the “break” phase includes the deletion of the preexistent SFs on the old wireless link.

The twofold interaction between the control plane and the application plane, on the one hand, and between the control plane and the transport plane, on the other, is of great importance: the former allows the acquisition of the application QoS requirements for the resource control during the session setup and tear-down phases, while the latter enables the control plane to modify the resource allocation during the handover. Mobility management is based on MIP protocol, or one of its variants – Proxy MIP (PMIP) and/or Fast MIP (FMIP) protocols, and on the IEEE 802.21 framework that enables MIHs. The IEEE 802.21 framework defines an abstraction layer for the unified interaction between the upper layer entities, called MIH Users (MIHU), and the lower layer entities through a common interface. The mobility management framework includes several instances of the MIH Function (MIHF), defined as one of the services provided by the WXLM. MIHF hides all technology dependent messages and procedures from the MIHUs exposing only a set of standardized interfaces that can be used to exchange common messages like events, commands or notifications among local or remote MIHUs and the WiMAX system [178].

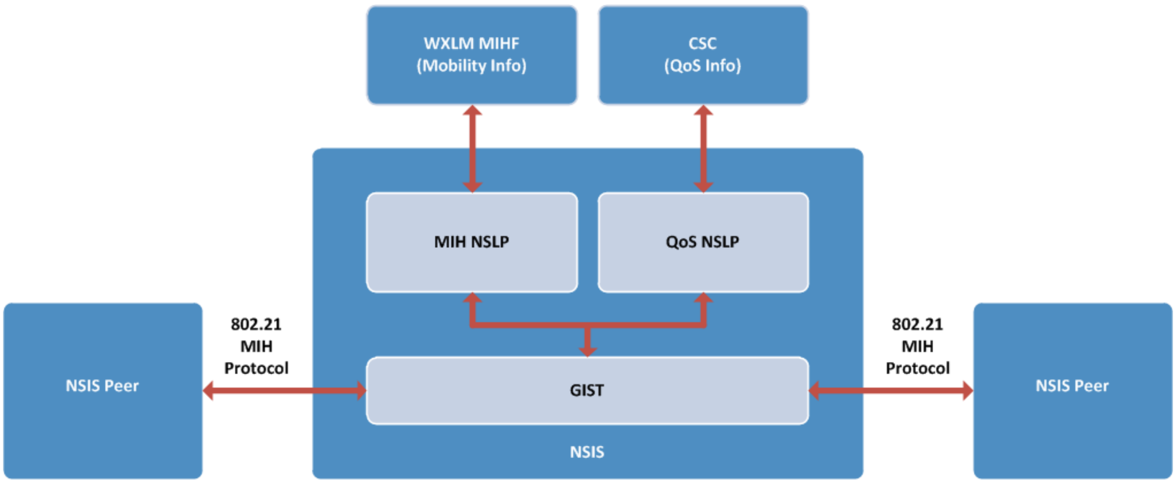

Figure 5-1: NSIS functional decomposition (QoS and MIH NSLPs)

MIHF also handles the exchange of the MIH protocol messages between remote MIHUs providing three different services: Media Independent Event Service (MIES), Media Independent Command Service (MICS) and Media Independent Information Service (MIIS). The MIH events originate from the WiMAX system and include information about the WiMAX link layer, for example, the respective link status. The MIH commands originate at the MIHUs and are used to convey the handover decisions. The transport of the MIH protocol messages between remote MIHF peers is supported by the NSIS framework through the MIH NSIS Signaling Layer Protocol (MIH NSLP), as specified in section 5.3, and GIST protocol. The MIH NSLP was developed as an extension to the NSIS framework in order to transport the MIH protocol messages. There are two main reasons to sustain this approach. First, the IEEE 802.21 proposed standard does not specify any protocol for message exchange, providing only the requirements for such protocol, namely, security and reliability. Second, QoS signaling, which is tightly coupled with mobility, is performed through the QoS-NSLP. In this context, the use of the NSIS framework to support both QoS and mobility procedures becomes the natural choice, since it fulfills the requirements for MIH message exchange between remote entities [179].

As defined by the WiMAX Forum, two different WiMAX mobility scenarios are supported in the defined architecture:

- ASN anchored mobility (also known as micro-mobility): refers to the case when the MN handover occurs between two BSs controlled by the same ASN-GW, without changing the MN subnetwork and therefore maintaining the IP address. In this case the handover, data path and context functions defined by the WiMAX Forum are used to manage the handover procedures.
- CSN anchored mobility (also known as macro-mobility): refers to the case when the MN handover occurs between two BSs controlled by different ASN-GWs, therefore changing the MN subnetwork and consequently the MN IP address. The IETF mobility management protocols (MIP, PMIP and FMIP) are used to handle the IP address change during the handover. In this case the ASN anchored mobility procedures are required to manage the WiMAX link layer handover procedures before the IP mobility management protocols are used.

Figure 5-2 illustrates the two mobility scenarios supported by the architecture: ASN and CSN anchored mobility. In the former case, mobility management is made within the ASN, whereas in the latter case the CSN involvement is necessary to manage the IP mobility using the IETF mobility management protocols – MIP, PMIP or FMIP.

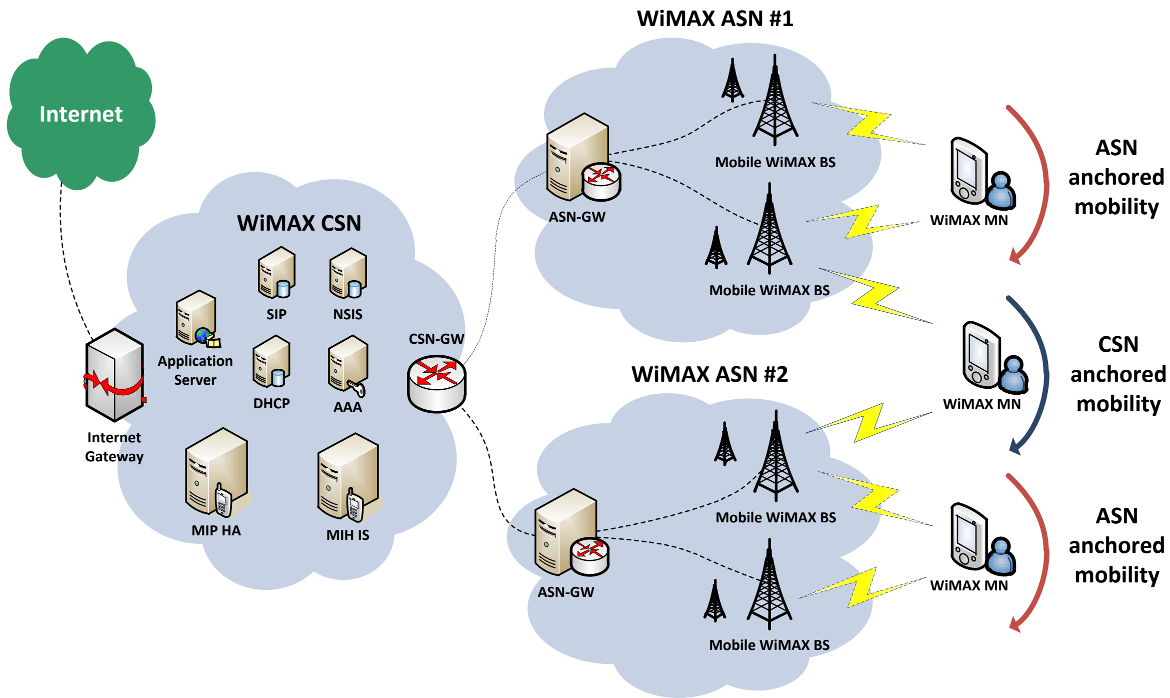

Figure 5-2: Supported WiMAX mobility network scenarios

5.1.2. Architecture Details

The proposed WiMAX QoS and mobility enabled architecture is illustrated in Figure 5-3.

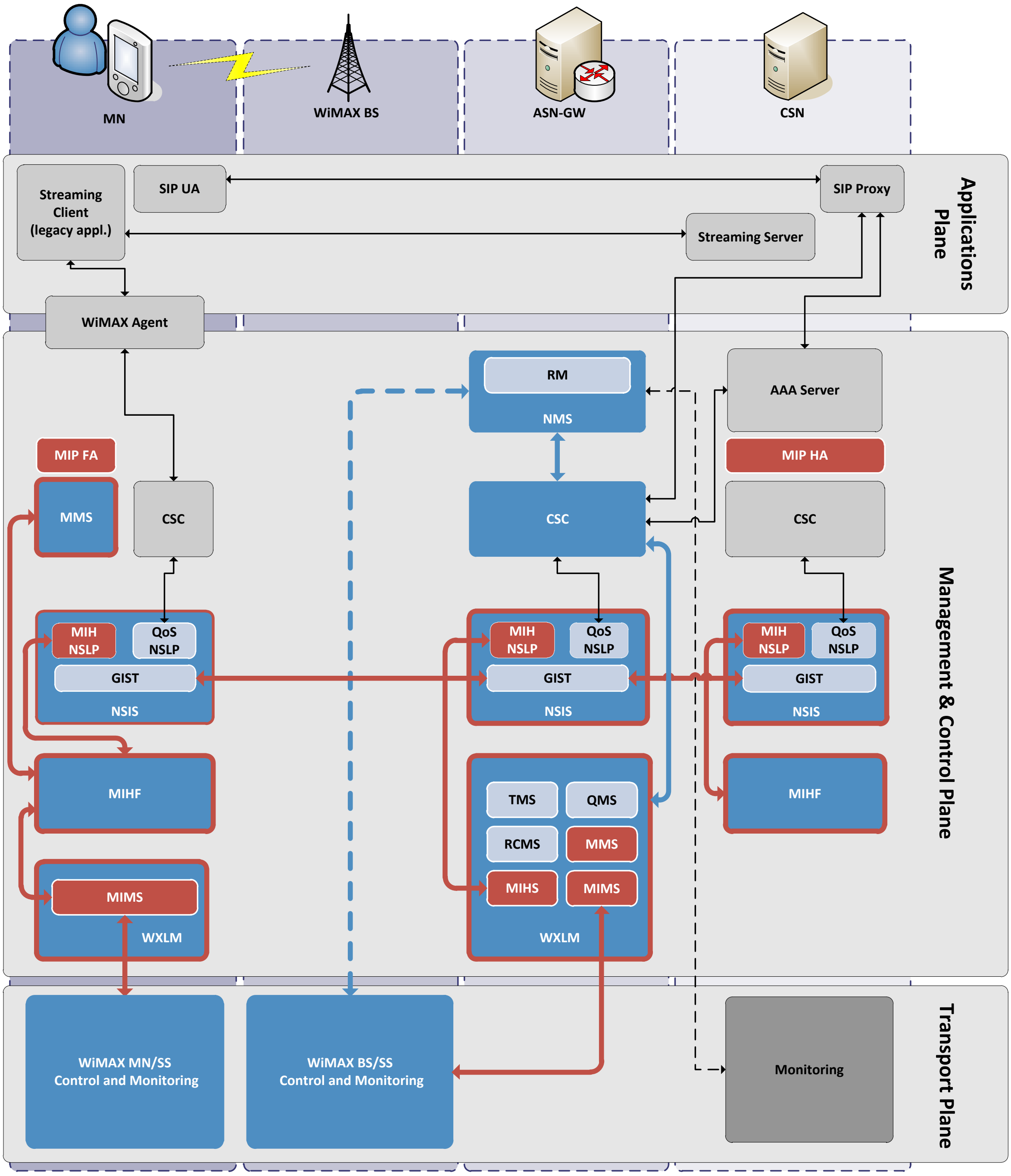

Figure 5-3: WiMAX mobility & QoS architecture

The WXLM is the main entity from the mobility management architecture. It includes a set of services to select the best target network for the handover procedure (MMS), as well as it provides a standardized media independent interface with the link layer (MIHS). The management of the handovers and the corresponding resource update follow the same approach of the resource reservation control during the session setup and teardown phases. All handover procedures are handled by the joint action of the CSC and the WXLM mobility-related services. In particular, the MMS handles the status of the network connections of the corresponding MN through the events received from the MIHS module and detects imminent handovers, taking active decisions and triggering the resource updating. This reconfiguration is controlled by the CSCs, which are able to retrieve from its internal state all the required information about the running sessions involved in the planned handover and, in particular, the WiMAX resources associated to the active data traffic flows that must be re-allocated.

The resource updating for mobility follows the make-before-break approach and is completely transparent to the application layer. When the MMS receives a new MIHS link layer event for a connection that is currently carrying data traffic, it initiates the required handover procedures and resources reconfiguration at the WiMAX and IP level. At the end of the resource allocation process, the MMS sends an MIHS command to the WiMAX link layer so that the handover procedure can proceed. After the handover preparation procedures are finished, a specific link layer event received by the MMS indicates that the association and connection to the target WiMAX BS is completed. Thereafter the mobility management protocol is triggered to perform the handover at the IP level using MIP. Finally, data traffic is mapped to the SFs allocated on the target BS and the resources allocated in the previous WiMAX BS are released. Further details about the WiMAX handover are provided in the following sections, including detailed signaling messages for the whole handover procedure.

The proposed architecture was developed within the framework of the European IST collaborative project WEIRD. The architecture modules and interfaces designed and developed under the scope of this thesis are highlighted in *red* in Figure 5-3, more precisely, the WXLM mobility services (MMS and MIHS), as well as the MIH NSLP to transport the IEEE 802.21 protocol messages.

5.2. WiMAX Cross Layer Manager Mobility Related Services

Section 4.3 presented the WXLM, which main objective was to facilitate the communications, from a QoS point of view, between the network and the WiMAX link layer. To achieve this objective, the following services were thoroughly depicted:

- Terminal Management Service (TMS): terminal states (normal, sleep and idle) and status (on and off) management, as well as control of network entry and exit procedures – more information on section 4.3.2;
- QoS Management Service (QMS): service flows management (admission control, provisioning, reservation, modification and deletion – more information on section 4.3.3;
- Radio Channel Management Service (RCMS): radio channel information management (radio resources occupancy and SS/MN physical measurements) – more information on section 4.3.4;
- Media Independent Management Service (MIMS): WiMAX equipments interfaces management (standardized and proprietary interfaces) – more information on section 4.3.5.

This section, as illustrated in Figure 5-4, proposes two novel WXLM cross-layer services to optimize the mobility procedures in WiMAX. One of the new services defined is the MIHS, which provides standardized and media independent interfaces, based on the IEEE 802.21 framework, to communicate with the WiMAX link layer. The second new WXLM service is the MMS, which is responsible to manage all the handover procedures and phases, including the handover triggering, preparation, decision and completion phases. Both the MIHS and the MMS run on both instances of the WXLM, either at the terminal or on the network side. Furthermore, the MIMS is also extended with support for an IEEE 802.21 compliant interface.

Table 5-1 summarizes the mobility-related services provided by the WXLM.

Table 5-1: WXLM mobility services

WXLM Management Service	Description
Mobility (MMS)	Control of the handover context transfer between the serving and the target WiMAX links
Media Independent Handover (MIHS)	Implements the IEEE 802.21 Media Independent Handover Function (MIHF)

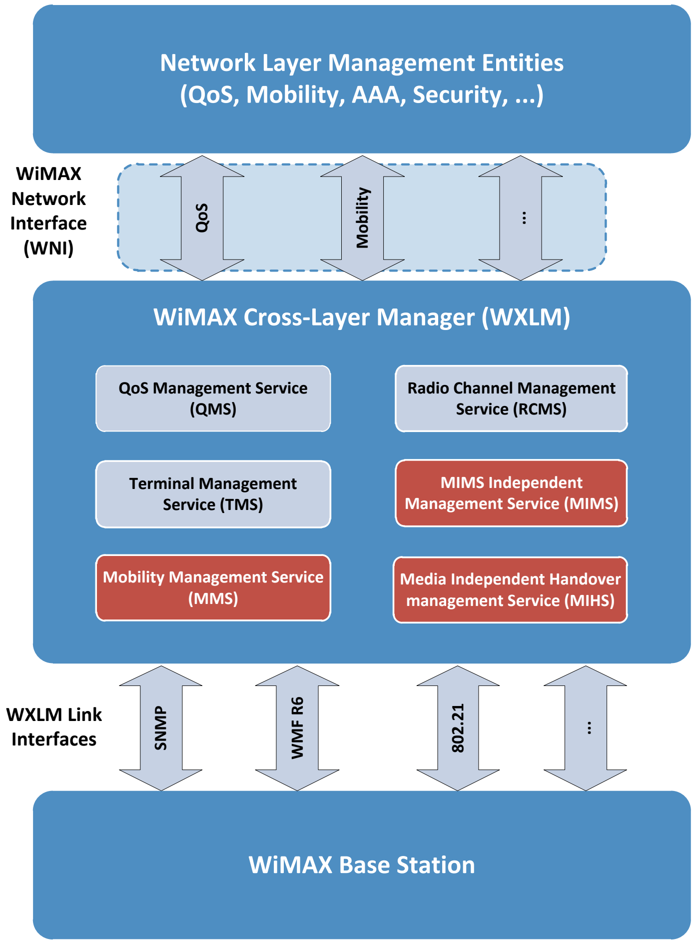

Figure 5-4: WXLM mobility services

Hereafter the WXLM MMS and the MIHS services will be detailed in sections 5.2.1 and 5.1.2, respectively.

5.2.1. WXLM Media Independent Handover Management Service

The IEEE 802.21 standard aims to optimize the mobility management procedures in heterogeneous access environments. Towards this aim, it defines the MIH framework, which provides standardized interfaces between the access technologies and the mobility protocols from the higher layers in the protocol stack. IEEE 802.21 introduces a new entity called MIH Function (MIHF), which hides the specificities of different link layer technologies from the higher layer mobility entities. Several higher layer entities, known as MIHUs can take advantage of the MIH framework, including mobility management protocols, such as FMIP, PMIP and SIP, as well as the other mobility decision algorithms. In order to detect, prepare and execute the handovers, the MIH platform provides three services:

- *MIES*: provides event reporting such as dynamic changes in link conditions, link status and link quality. Multiple higher layer entities may be interested in these events at the same time, so these events may need to be sent to multiple destinations;
- *MICS*: enables MIHUs to control the physical, data link and logical link layer. The higher layers may utilize MICS to determine the status of links and/or control a multimode terminal. Furthermore, MICS may also enable MIHUs to facilitate optional handover policies. Events and/or commands can be sent to MIHUs within the same protocol stack (local) or to MIHUs located in a peer entity (remote);

- *MIIS*: provides a framework by which a MIHF located at the MN or at the network side may discover and obtain network information within a geographical area to facilitate handovers. The objective is to acquire a global view of all the heterogeneous networks in the area in order to optimize seamless handovers when roaming across these networks.

Figure 5-5 illustrates some examples of the IEEE 802.21 event and command services in a WiMAX environment. The figure depicts the following WiMAX link layer events and commands:

- *Link_Parameters_Report* event: provides information about the WiMAX link layer parameters; it can be sent periodically to the upper layers, or it can be sent when a specific threshold is surpassed;
- *Link_Down* event: indicates the upper layers that the WiMAX link layer is disconnected;
- *Link_Up* event: indicates the upper layers that the WiMAX link layer is connected;
- *Link_Action* command: notifies the WiMAX link layer to perform a specific action, in this case to scan the wireless link.

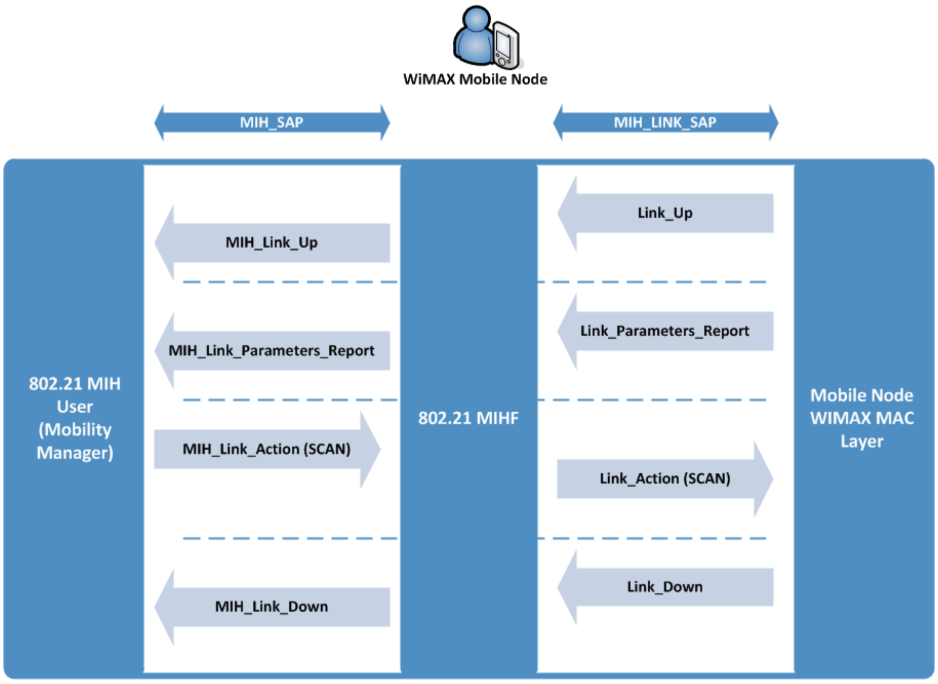

Figure 5-5: 802.21 procedures on a WiMAX MN

In order to optimize mobility procedures, it is important to integrate cross-layer mechanisms and provide the higher layer mobility management protocols with the required link layer information. For example, in order to trigger the handover process, mobility management protocols should obtain information about the current link states and available networks in order to improve their decision making process. The IEEE 802.21 framework, extended with a new set of commands and events, and integrated with the already existing WiMAX mechanisms for mobility, is able to significantly enhance the mobility procedures in WiMAX ANs.

The MIHS main objective is to integrate the IEEE 802.21 cross-layer mechanisms in WiMAX networks. It implements the core of the IEEE 802.21 framework – the MIHF, as well as the IEEE 802.21 events (MIH Event Service Manager – MESM), commands (MIH Command Service Manager – MCSM) and information (MIH Information Service Manager – MISM) services management. Figure 5-6 depicts the MIHS.

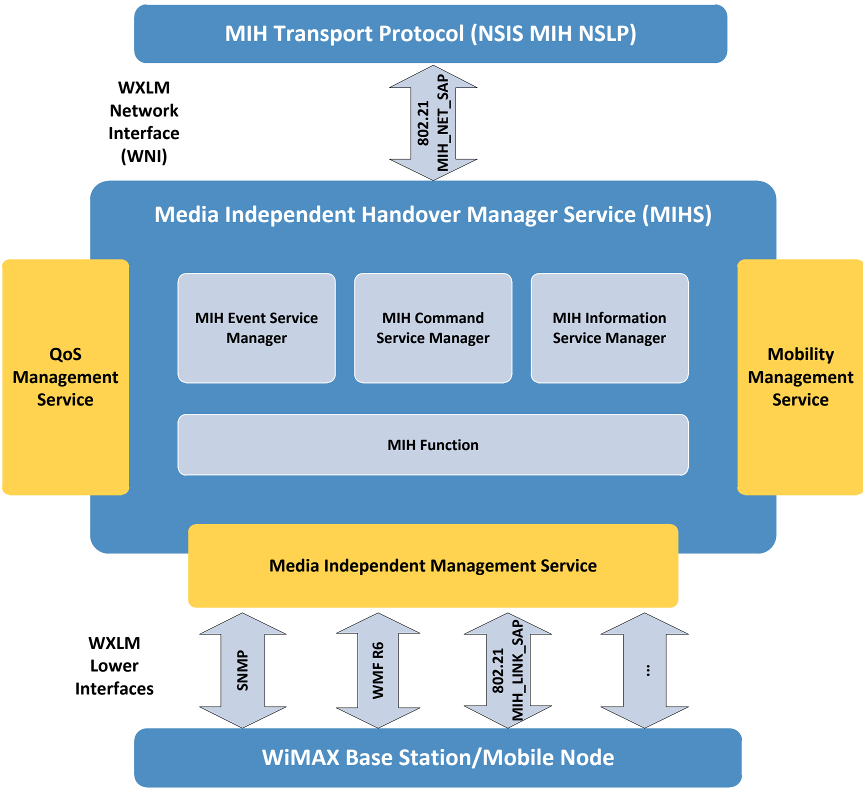

Figure 5-6: WXLM Media Independent Handover management Service (MIHS)

Table 5-2 presents the 802.21 primitives supported by the proposed architecture.

Table 5-2: IEEE 802.21 primitives (events, commands and information) supported by the WXLM MIHS

Event Service	Command Service	Information Service
Link_Detected	*Link_Capability_Discover*	*Get_Information*
Link_Down	*Link_Event_Subscribe*	
Link_Up	*Link_Configure_Thresholds*	
Link_Going_Down	*Link_Get_Parameters*	
Link_HO_Imminent		
Link_HO_Complete		
Link_Parameters_Report		

Besides the standardized 802.21 primitives previous in the table above, it was necessary to define new actions for the *Link_Action* command in order to fully integrate the WiMAX AN. Table 5-3 provides further details about the novel actions defined for the *Link_Action* primitive.

Table 5-3: New IEEE 802.21 commands defined by the WXLM MIHS

802.21 Primitive	Action Name	Description
MIH_Link_Actions & *Link_Action (request / confirm)*	*HO_PREPARE*	Triggers the handover preparation phase on the MN side. As a consequence the WiMAX link layer triggers an *MOB-MSHO-REQ* message towards the WiMAX BS
	HO_CONFIRM	Triggers the handover confirmation phase on the MN side. Indicates the WiMAX link to trigger an *MOB-HO-IND* link layer message towards the WiMAX BS

Further details about the usage and integration of the IEEE 802.21 primitives described in Table 5-2 and Table 5-3 are provided in section 5.4 with a set of message signaling diagrams that illustrate the complete handover procedure.

5.2.2. WXLM Mobility Management Service

Hard Handover (HHO) and Soft Handover (SHO) methods are supported by mobile WiMAX, as defined in IEEE 802.16e. In the HHO method or *break-before-make* approach, the serving network link is broken before the handover execution is triggered and the target link is established. With respect to the SHO method or *make-before-break* approach, the target link is prepared and established before the serving network link is broken and the handover is executed. Although the SHO method provides continuous connectivity for the MN, it is much more complex and requires backbone communication between the serving and the target access technologies. The overall WiMAX mobility procedure, including the IEEE 802.16e and WiMAX Forum related messages, is illustrated in Figure 5-7.

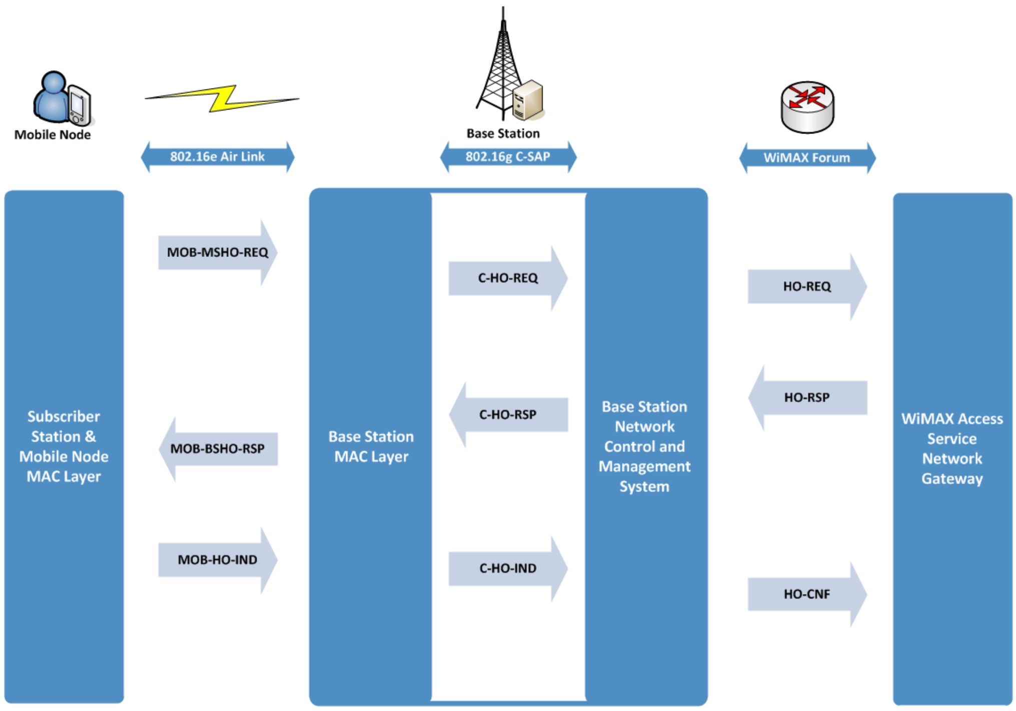

Figure 5-7: Mobility procedures in IEEE 802.16e/g and WiMAX Forum

Seamless handover mechanisms require strong cooperation between a set of complementary phases that must occur before, during and after the mobility process. In detail, prior to the handover, it is crucial to detect at the correct moment when the handover procedures shall be triggered. This moment, also known as handover initiation phase, can be triggered either by the terminal itself, for example, due to user movement, or by the network side entities because of network congestion reasons. After the handover procedures are activated, it is required to effectively prepare the handover by detecting, selecting and preparing the most appropriate Candidate AN (CAN) for the handover. Thereafter, the handover execution is performed moving the packets from the old access interface to the new access interface.

The WXLM MMS is responsible for controlling all the identified handover phases, including the always-critical target network selection, as well as the interfaces with the mobility and QoS management protocols. From the architecture point of view, the MMS is distributed on the network and on the terminal side, enabling mobile and network initiated handovers.

Figure 5-8 illustrates the MMS components, namely the Thresholds Configuration Manager (TCM), Handover Decision Manager (HDM), Network Discovery Manager (NDM) and Handover Resources Manager (HRM), as well as the interactions with the remaining WXLM services.

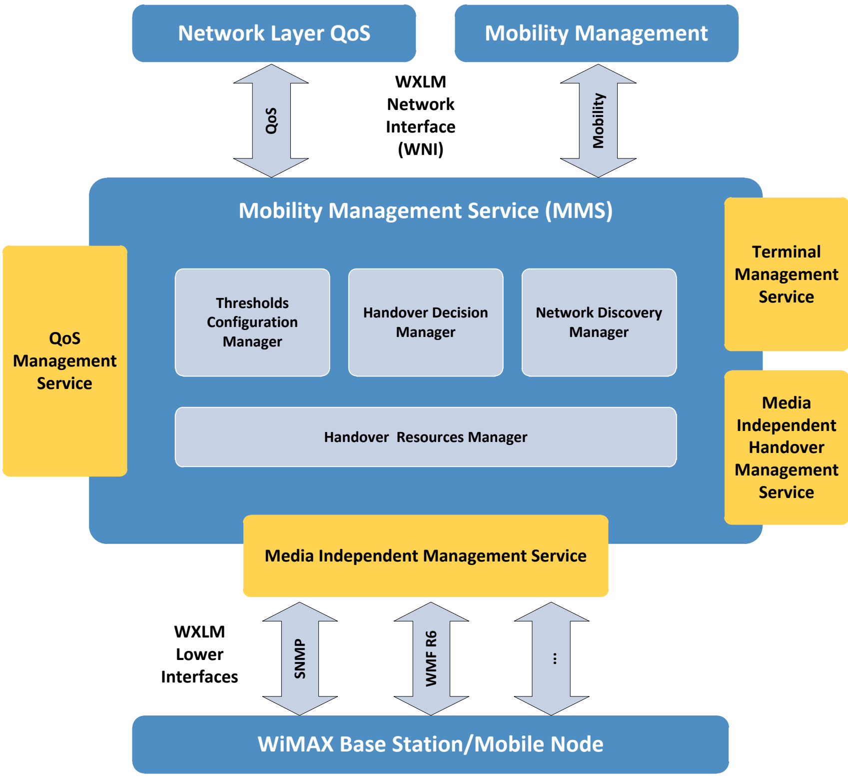

Figure 5-8: WXLM Mobility Management Service (MMS)

The TCM is responsible for preparing and configuring the WiMAX link layer for the handover procedure. It uses IEEE 802.21 procedures to discover the link layer capabilities, subscribe the link layer events and configure the link layer thresholds. When the configured thresholds are crossed, the WiMAX link layer generates an IEEE 802.21 event primitive towards the MMS, either local or remote. Thereafter the handover procedure is initiated through the following steps:

- Neighbor WiMAX ANs discovery: this process is controlled by the NDM, which uses the IEEE 802.21 MIIS to obtain the WiMAX links surrounding the MN;
- Candidate WiMAX ANs resources availability check: this process is controlled by the HRM and verifies the available resources on each one of the neighbor WiMAX links; WiMAX Forum procedures (*HO-REQ/RSP*) are used on the backbone to establish the communication between the serving and the candidate ASN-GWs;
- Candidate WiMAX AN selection: decide on the most appropriate WiMAX candidate network to perform the handover procedure; this process is performed by the HDM;
- QoS resources allocation: establish the required QoS resources in the WiMAX wireless link, as well as on the wired path between the ASN-GW and the BS; for macro-mobility scenarios, as identified in Figure 5-2, it is also necessary to enforce QoS mechanisms on the backbone side of the network through NSIS, more precisely between the core and the ASN-GW; after the MN attachment to the

candidate WiMAX AN; WiMAX Forum procedures (*HO-CNF*) are used on the backbone to establish the communication between the serving and the candidate ASN-GWs; this process is performed by the HRM;

- Layer 3 mobility management protocol trigger: in macro-mobility scenarios, after the connection to the TAN is finalized, the HRM triggers the mobility management protocol to initiate the IP address management on the MN; client-side and network-side mobility management protocols are supported, such as MIP and PMIP, respectively; this process is performed by the HRM;
- QoS resources removal: when the handover process is finished, the QoS resources on the previous WiMAX link must are removed; this process is controlled by the HRM.

5.3. NSIS for MIH Transport Mechanism

In order to improve the handover between heterogeneous ANs, the IEEE 802.21 standard is defined to provide media independent handover services. IEEE 802.21 makes available link layer information to the upper network layers, both locally and remotely. Although the standard defines the guidelines to transport the MIH protocol messages between remote entities, namely the need to be reliable and to guarantee security of the exchanged messages, it does not specify a transport mechanism.

The IETF NSIS working group has already finalized the base protocols to offer flexible and extensible signaling services for a variety of applications, including the GIST to support secure, reliable, congestion-controlled data transport, as well as other features desired for signaling. Given the potential of NSIS to perform QoS signaling for real-time applications in wired and wireless scenarios, which is also often desired by the applications using MIH, herein it is proposed, together with University of Coimbra, Nextworks and University of Groningen, to use GIST to transport MIH messages. Therefore, it is defined a MIH NSIS Signaling Layer Protocol (MIH NSLP) to support seamless mobility in heterogeneous network environments through the integration of MIH and NSIS [178]. This specification was presented as an IETF draft [179].

The MIHFs might be spread in several network elements inside the same domain, or even across different domains. Figure 5-9 illustrates two different domains. Each domain is composed by the CN, responsible for the overall management and control of the network, connected to several ANs. Each AN provides connectivity to the MNs, using the WiMAX link. As depicted in Figure 5-9, each one of these entities – CN, AN and MN – is a potential candidate to host the MIHF entity. Therefore, MIH messages shall be able to reach all the MIHFs in the network, independently of their location.

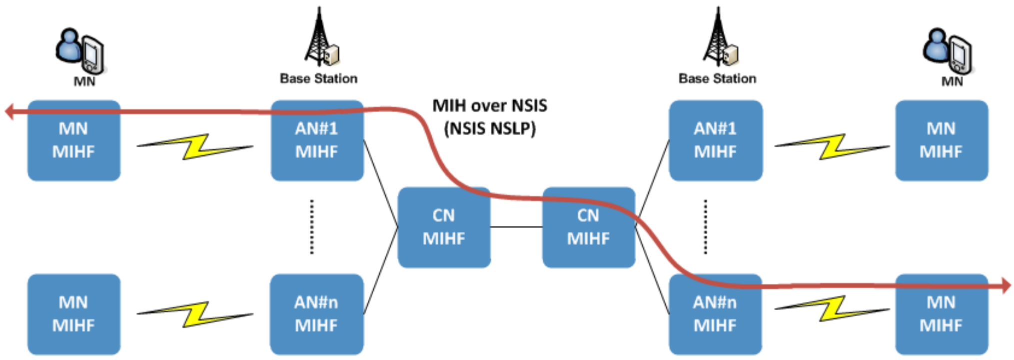

Figure 5-9: MIHF communication model

However, no specific transport mechanism is defined to carry the MIH protocol messages between remote MIHFs. Only the guidelines to transmit the MIH messages across the network are defined in the MIH standard. The transport protocol used must be reliable, guaranteeing the correct delivery of the messages to the peer MIHF, and provide security over the exchanged messages.

The Transmission Control Protocol (TCP) is able to satisfy the reliability requirement posed by the MIH protocol. It provides error control and flow control, guaranteeing the in-order delivery of the packets. However, although TCP offers reliability, it does not guarantee fast-packet delivery due to its retransmission mechanism. In what concerns the User Datagram Protocol (UDP), it assures fast-packet delivery, but it does not guarantee the correct packet delivery, and therefore is unreliable.

As a result, a reliable, secure and fast-delivery solution to transport MIH protocol messages between peer MIHFs is required. Although a new fast-delivery solution can be designed, other existent solutions can be envisioned.

To address seamless mobility support, media independent handovers together with fast/local mobility approaches are not sufficient. When users move while accessing real-time services, resources need to be reserved in advance in the new network to guarantee that the services maintain their quality. NSIS QoS signaling protocol is an emergent QoS signaling and reservation protocol with capabilities to be used in mobile environments. NSIS decomposes the overall signaling protocol suite into a generic (lower) layer and specific upper layers for each specific signaling application. In the lower layer, GIST offers transport services to higher layer signaling applications for two purposes: sending and receiving signaling messages between neighbor hops (NSIS entities), and exchanging control and feedback information. Above this layer, there is the NSLP layer, which generically stands for any protocol within the signaling application layer.

NSIS is very well suited for heterogeneous wired and wireless networks and is able to interact with mobility protocols for seamless handovers. Therefore, to enable the support of seamless mobility, MIH can be integrated with NSIS and cooperate in the handover process. To provide a clean cooperation with low overhead (both in messages exchanged and time), and since MIH protocol messages require a transport protocol, herein it is proposed and defined a MIH NSLP to use NSIS as a transport protocol for MIH messages.

5.3.1. Media Independent Handover NSLP Specification

In order to use the NSIS framework to transport MIH messages, a specific NSLP, the MIH NSLP, is proposed. The MIH NSLP allows the distribution of MIH messages across different networks. The following section describes the procedure to transport MIH messages within the MIH NSLP, followed by the specification of the MIH NSLP architecture.

5.3.1.1. MIH NSLP Architecture

The MIH NSLP is responsible for the transport of MIH messages using the GIST protocol. Figure 5-10 illustrates the architecture of NSIS usage as the MIH transport protocol, and more specifically the interaction between the MIH NSLP, the MIHF and the GIST protocol.

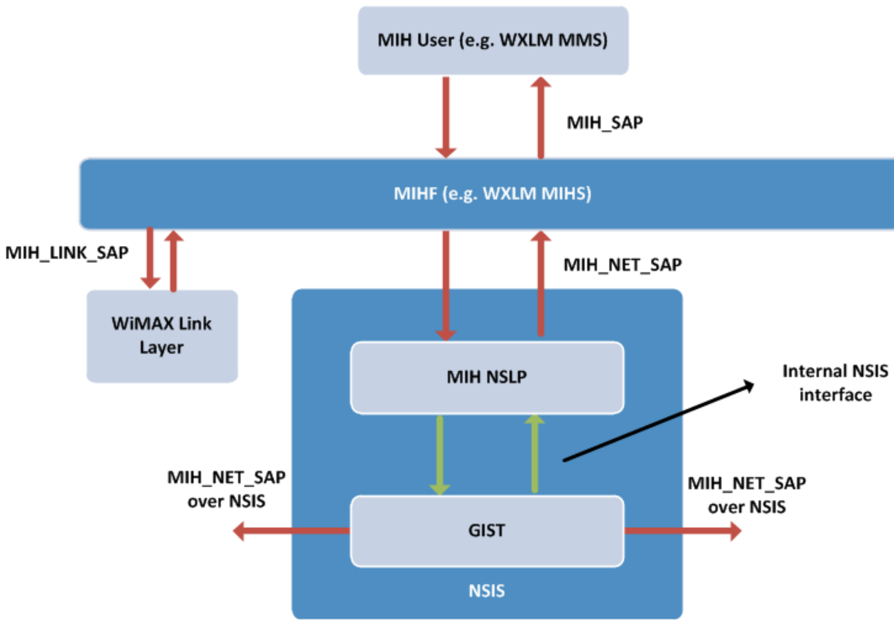

Figure 5-10: MIH NSLP architecture

The MIH NSLP interface with the MIHF handles the MIH protocol messages exchange. This interface is compliant with the Media Independent Handover Network Service Access Point (MIH_NET_SAP) defined in [39].

The MIH NSLP interface with GIST handles message transport. The MIH NSLP is split in six different functionalities as follows:

- Interface with MIHF;
- Interface with GIST;
- Message transport (and retransmission if acknowledge is required);
- Message reception;
- Message interception;
- MIH Information Server (IS):
    - Registration;
    - Deregistration;
    - Request;
    - Messages retransmission.

These functionalities are described in the next sections.

5.3.2. MIH Message Transport

To be able to transport the MIH messages, NSIS requires the destination network address of the destination MIHF. However, MIH entities only handle MIHF Identifiers (ID) to identify the remote MIHF. Therefore, there is the need to perform the mapping between the MIHF ID and the correspondent network addresses, which is under NSIS responsibility.

The main functionality of the MIH NSLP is to handle the mapping between MIHF ID and network addresses, since GIST is able to provide all the required functionalities required by the MIH specification for the MIH message transport.

Figure 5-11 shows the procedure to send MIH messages to the remote MIHF when the remote MIHF IP address is available, either through the cache mechanisms or resorting to the mapping procedure. In this figure the MIH message needs to be sent from the source MIH NSLP to the destination MIH NSLP. To send the MIH message, the MIH NSLP creates an *NSIS_Data* message with the MIH message as one of its components.

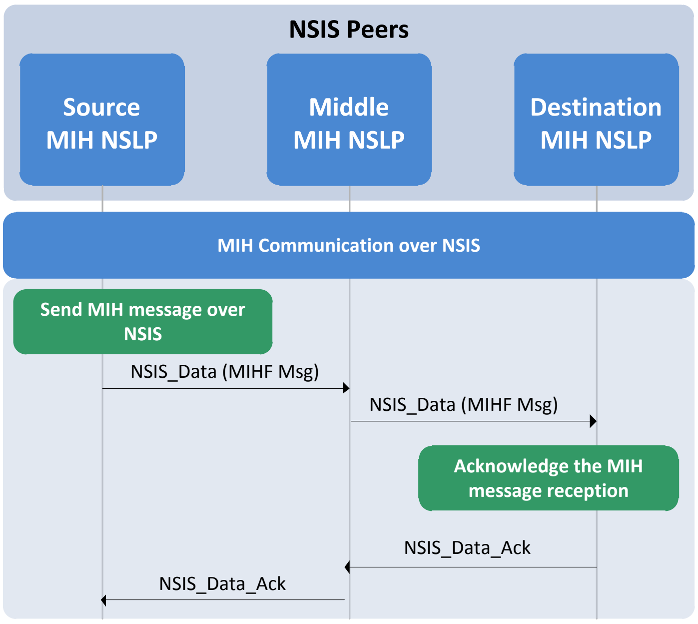

Figure 5-11: Message transport between two MIH NSLPs

During the message exchange, the *NSIS_Data* message is intercepted by the middle MIHF. According to the MIH NSLP architecture, this feature could be useful for several scenarios. If no specific action is defined in the middle MIHF entity, the MIH NSLP must forward the *NSIS_Data* message to the destination MIH NSLP.

When an *NSIS_Data* message reaches the destination, the MIH message is forwarded to the local MIHF for processing. The MIH message information is transparent to the MIH NSLP. Optionally, an *NSIS_Data_Ack* message can be sent to the source MIH NSLP when the *NSIS_Data* message arrives to the destination MIH NSLP. This feature can be requested by the source MIH NSLP and should depend on the transfer attributes requested to GIST (reliable and/or secure).

5.3.3. MIH NSLP Registration

In order to map the MIHF ID into a network addresses it is required to query a server which aggregates this information. To achieve this goal an extension to the 802.21 MIIS IS is proposed, enhancing it with a set of mechanisms to map the MIHF ID and its IP network address. Therefore the MIH IS is responsible for handling the mapping between the ID and the network addresses of the MIHF entities.

With the usage of the MIH IS, when a MIH NSLP needs to send a MIH message to a remote MIHF, it queries the MIH IS in order to retrieve the appropriate network address. Figure 5-12 describes the procedure that a MIH NSLP performs to register/deregister itself on/from the MIH IS.

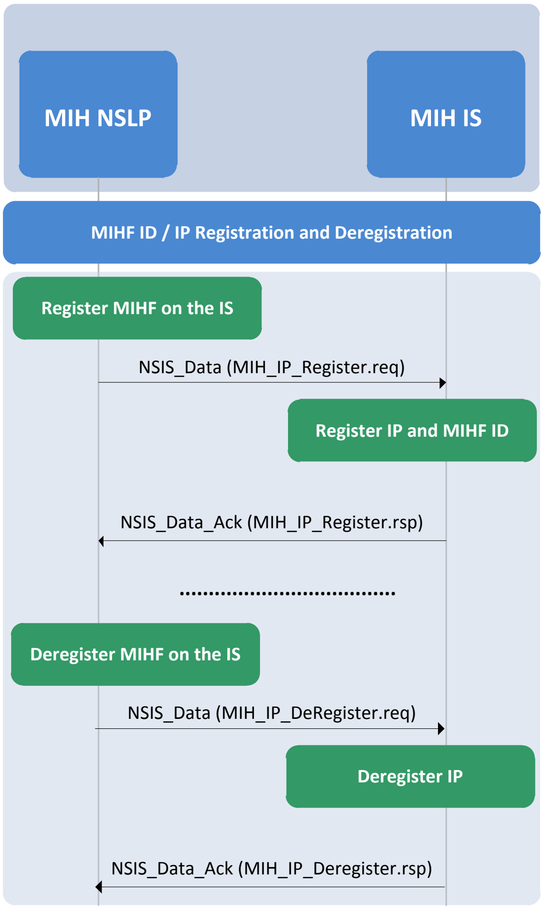

Figure 5-12: MIH NSLP registration/deregistration in a MIH registration server

This registration procedure is composed by two new MIH messages, the *MIH_IP_Register* and the *MIH_IP_Deregister*. The *MIH_IP_Register.req* message is sent by the MIH NSLP to the MIH IS to register its MIHF ID and IP address. To confirm the registration of the MIH NSLP, the MIH IS sends an *MIH_IP_Register.rsp* to the MIH NSLP with the result of the registration. The registration result can be:

- *Successful*: the registration process was successful;
- *Warning due to duplicate MIHF ID*: the received MIHF ID already exists with a different IP address;
- *Warning due to duplicate IP Address*: the received IP address already exist with a different MIHF ID;
- *Internal failure*: an error occurred not related to the request received.

After a successful registration procedure the MIH IS is able to map this MIHF ID to the appropriate IP address and the MIH NSLP is ready to transport MIH messages.

The *MIH_IP_Deregister* message is sent to the MIH IS when the MIH NSLP intends to stop functions. This message includes the MIHF ID that is to be removed from the registry. The deregistration result can be:

- *Successful*: the deregistration process was successful;
- *Warning due to unknown MIHF ID*: the received MIHF ID does not exists;
- *Internal failure*: an error occurred not related to the request received.

Figure 5-13 describes the procedure that a MIH NSLP performs to map a MIHF ID to an IP address.

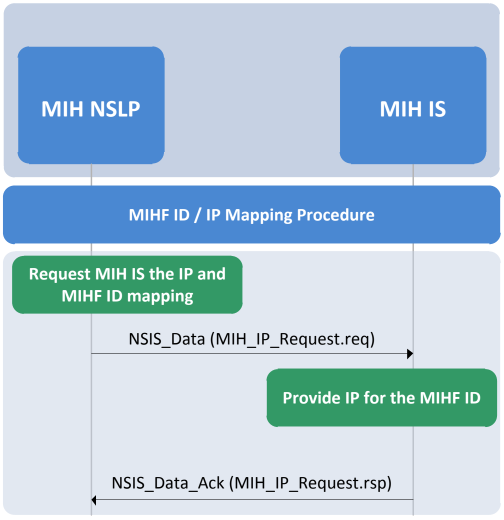

Figure 5-13: MIH NSLP mapping procedure

In this figure there are two MIH NSLP messages, the *MIH_IP_Request* and the *MIH_IP_Response*. The *MIH_IP_Request* message is sent from the MIH NSLP that requires the mapping to the MIH IS with the MIHF ID that needs to be mapped to an IP address. After the MIH IS mapping, an *MIH_IP_Response* message is sent from the MIH IS to the requesting MIH NSLP. This message includes the IP address that resulted from the mapping of the request MIHF ID.

In the MIHF ID mapping process some errors may occur. When an error occurs the MIH IS entity must send a *MIH_IP_Error* message to the requesting MIH NSLP stating the error. The possible errors are the following:

- Unknown MIHF ID: there is no reference to the requested MIHF ID;
- Unknown IP address: there is no IP address associated to the requested MIHF ID;
- Internal Error: an error occurred not related to the MIHF ID or the IP address.

Performance measurements related with the transport of the MIH messages with the NSIS protocol are provided in section 5.6.1.2.5.

5.4. Detailed WiMAX Handover Signaling Diagrams

In this section we depict the integration of IEEE 802.21 MIH framework with the WiMAX mobility procedures. A macro-mobility scenario is presented, with particular focus on the integration of the WXLM mobility (e.g. MMS, MIHS) and QoS (e.g. QMS, MIMS) related services with the IEEE 802.21 services, as well as with the NSIS QoS signaling protocol.

5.4.1. Handover Configuration Phase

In this phase all the procedures required to the configuration and preparation of the WiMAX link layer for mobility procedures is made. Namely, three different steps are defined (illustrated in Figure 5-14).

Step 1:

- The WXLM MMS, acting as an 802.21 MIHU, queries the MN WiMAX MAC layer to discover the list of supported events and commands (*MIH_Link_Capability_Discover.req*);
- The MN WiMAX MAC layer replies with the list of events and commands supported by the WiMAX link layer (*MIH_Link_Capability_Discover.rsp*).

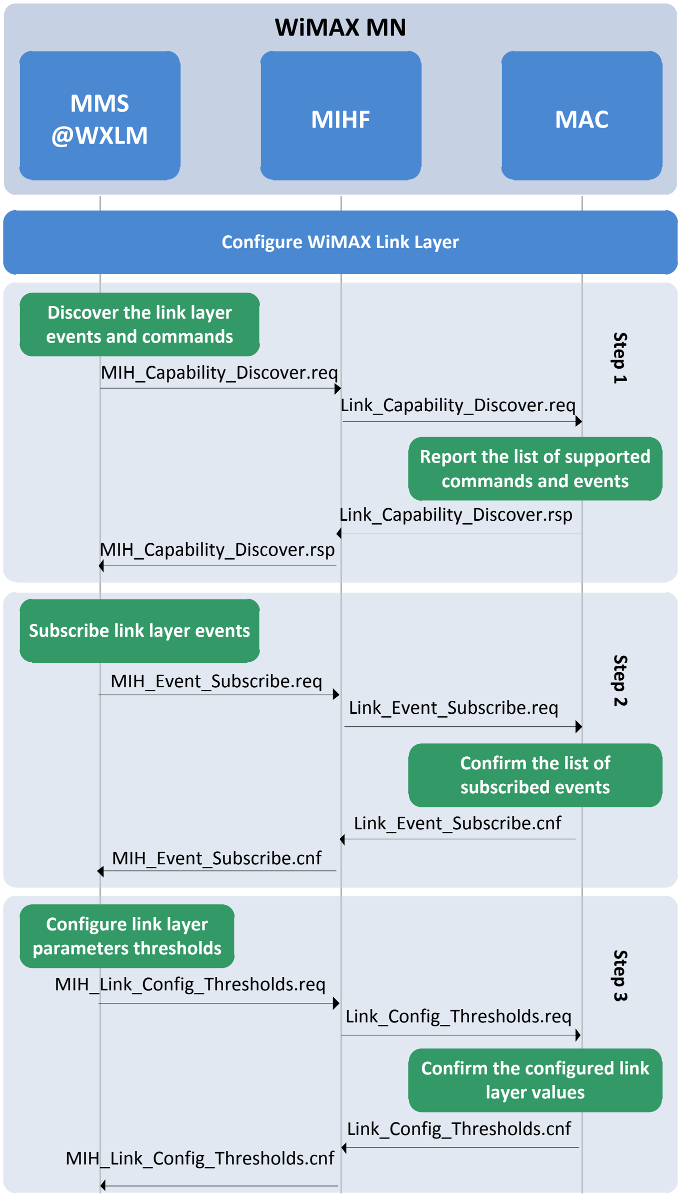

Figure 5-14: WiMAX macro-mobility scenario – link layer configuration

Step 2:

- Based on the list of events supported by the link layer, the MMS selects the set of events to subscribe;
- The *MIH_Link_Event_Subscribe.req/rsp* messages are used to inform the link layer about the set of events that the MMS is subscribing to.

Step 3:

- The MMS configures the thresholds of the WiMAX link layer events (*MIH_Link_Config_Thresholds.req/rsp*) and specifies the time interval between periodic reports for the *Link_Parameters_Report.ind* event.

Now, the WiMAX link layer is ready to trigger events to the MMS and initiate the handover procedure.

5.4.2. Handover Initiation Phase

This phase is responsible for initiating the handover procedures and is split in three steps (Figure 5-15).

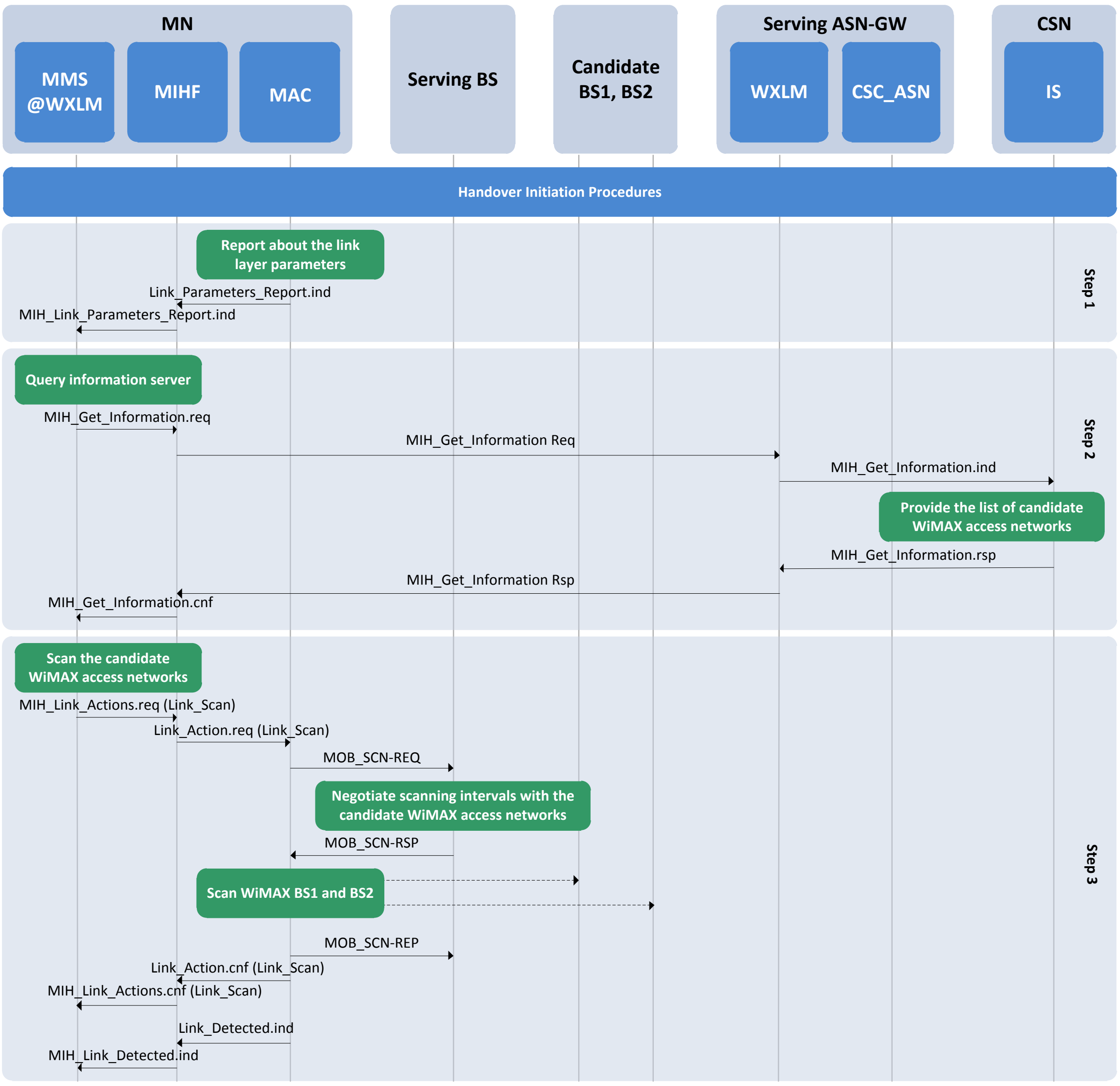

Figure 5-15: WiMAX macro-mobility scenario – handover initiation phase

Step 1:

- The MN triggers a *Link_Parameters_Report.ind* event due to a value that surpassed the configured threshold.

Step 2:

- Based on the *MIH_Link_Parameters_Report.ind* event received, the MMS queries the IEEE 802.21 IS to discover the surrounding WiMAX networks (*MIH_Get_Information.req/ind/rsp/cnf*).

Step 3:

- The MMS triggers an *MIH_Link_Action.req/cnf (Link_Scan)* command to the surrounding WiMAX networks;
- As a result, the WiMAX link layer negotiates scanning intervals for each candidate WiMAX network (*MOB_SCN-REQ/RSP*) and performs the scan procedure;
- IEEE 802.21 *Link_Detected.ind* events are triggered when the candidate WiMAX links are detected.

After the neighbor WiMAX ANs are identified and detected, the next phase is to prepare the handover.

5.4.3. Handover Preparation Phase

During this phase the required procedures to perform the handover are prepared. Two internal sub-phases are identified and described in sections 5.4.3.1 and 5.4.3.2.

5.4.3.1. Candidate WiMAX Access Networks Resources Check

During this sub-phase the MMS checks for the resources availability on the candidate WiMAX ANs. The following internal steps are identified (illustrated in Figure 5-16).

Step 1:

- The MMS triggers an *MIH_Link_Action (HO_Prepare)* command towards the MN WiMAX link layer;
- As a result, an 802.16e *MOB_MSHO-REQ* MAC management message is triggered by the MN towards the serving BS;
- Thereafter, for each candidate WiMAX network, the serving BS triggers a WiMAX Forum *HO_Req* message towards the WXLM of the candidate ASN-GW.

Step 2:

- The MMS on the candidate ASN-GW receives the *HO_Req* message and authenticates with the AAA (*WXLM_New_SS.req/rsp*, *QAR* and *QAA* Diameter messages);
- The MMS triggers the QMS to perform admission control and check for the resources availability on the WiMAX (*REP-REQ/RSP* MAC management messages) and on the backbone network segments (*WXLM_E2E_QoS_Query.req/rsp* and *NSIS_Query_Req/Rsp*);

Step 3:

- After collecting information about the resources availability in the candidate WiMAX ANs, the MMS at the candidate ASN-GW sends a WiMAX Forum *HO_Rsp* message to the serving BS;
- As a result, the serving BS triggers an 802.16e *MOB_MSHO-RSP* MAC management message to the MN;
- Finally a *Link_Action.cnf (HO_Prepare)* event is triggered towards the MMS at the MN.

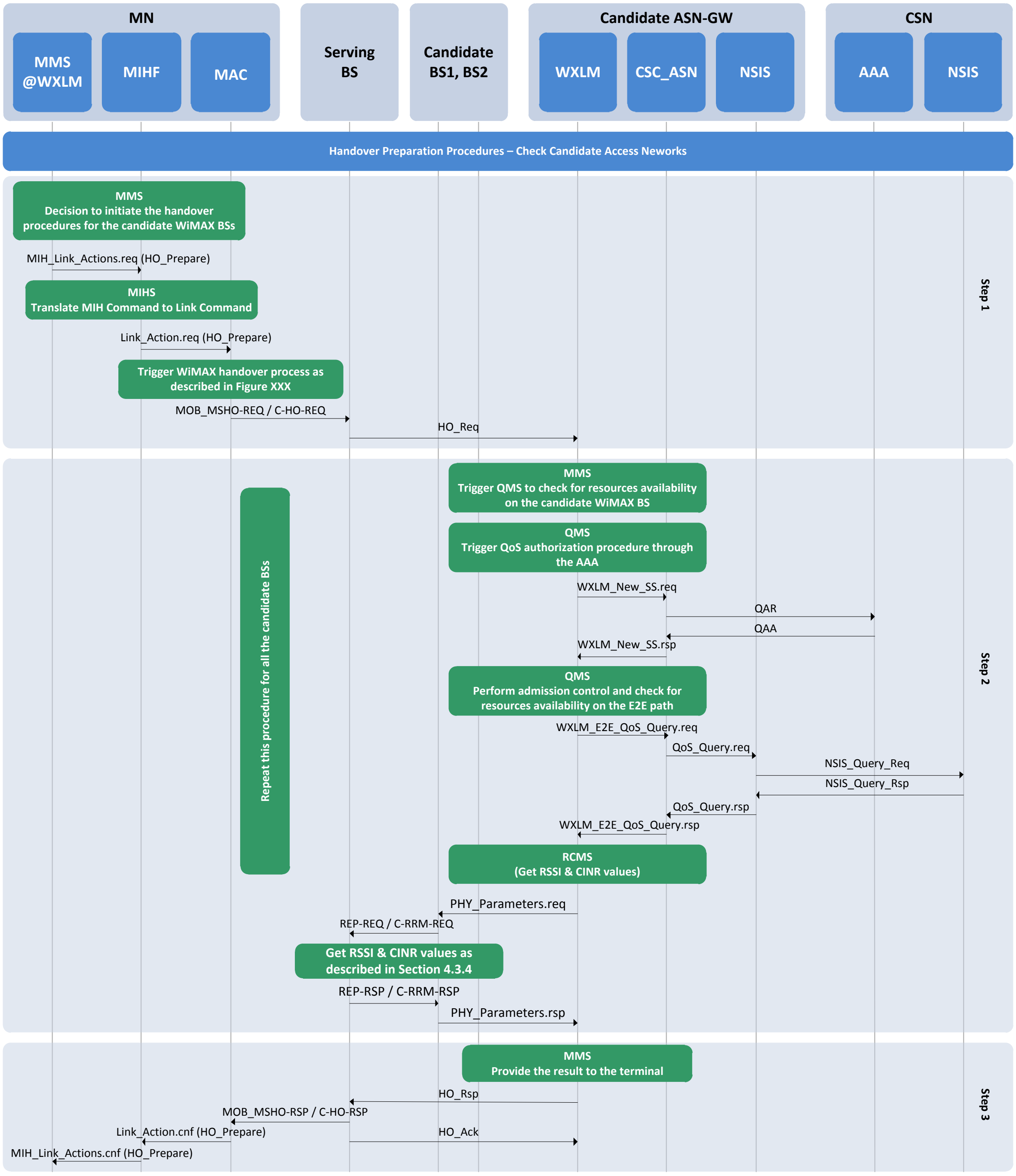

Figure 5-16: WiMAX macro-mobility scenario – resources availability check (handover preparation phase)

5.4.3.2. Target WiMAX Access Network Confirmation

During this sub-phase the MMS confirms the TAN for the handover procedure. The following internal steps are identified (illustrated in Figure 5-17).

Step 1:

- The MMS selects the target WiMAX AN for the handover and triggers an *MIH_Link_Action.req (HO_Commit)* command towards the MN link layer;
- Thereafter an 802.16e *MOB_HO-IND* MAC management message is sent to the serving BS, which subsequently triggers an WiMAX Forum *HO_Cnf* message to the target ASN-GW.

Step 2:

- The MMS at the target ASN-GW triggers the QMS to provision the SFs on the WiMAX link (*DSA-REQ/RSP* MAC management messages).

Step 3:

- The MN WiMAX link layer generates a *Link_Handover_Imminent.ind* and a *Link_Down.ind* event to the MMS at the MN indicating that the handover execution is imminent and that the WiMAX link is down, respectively.

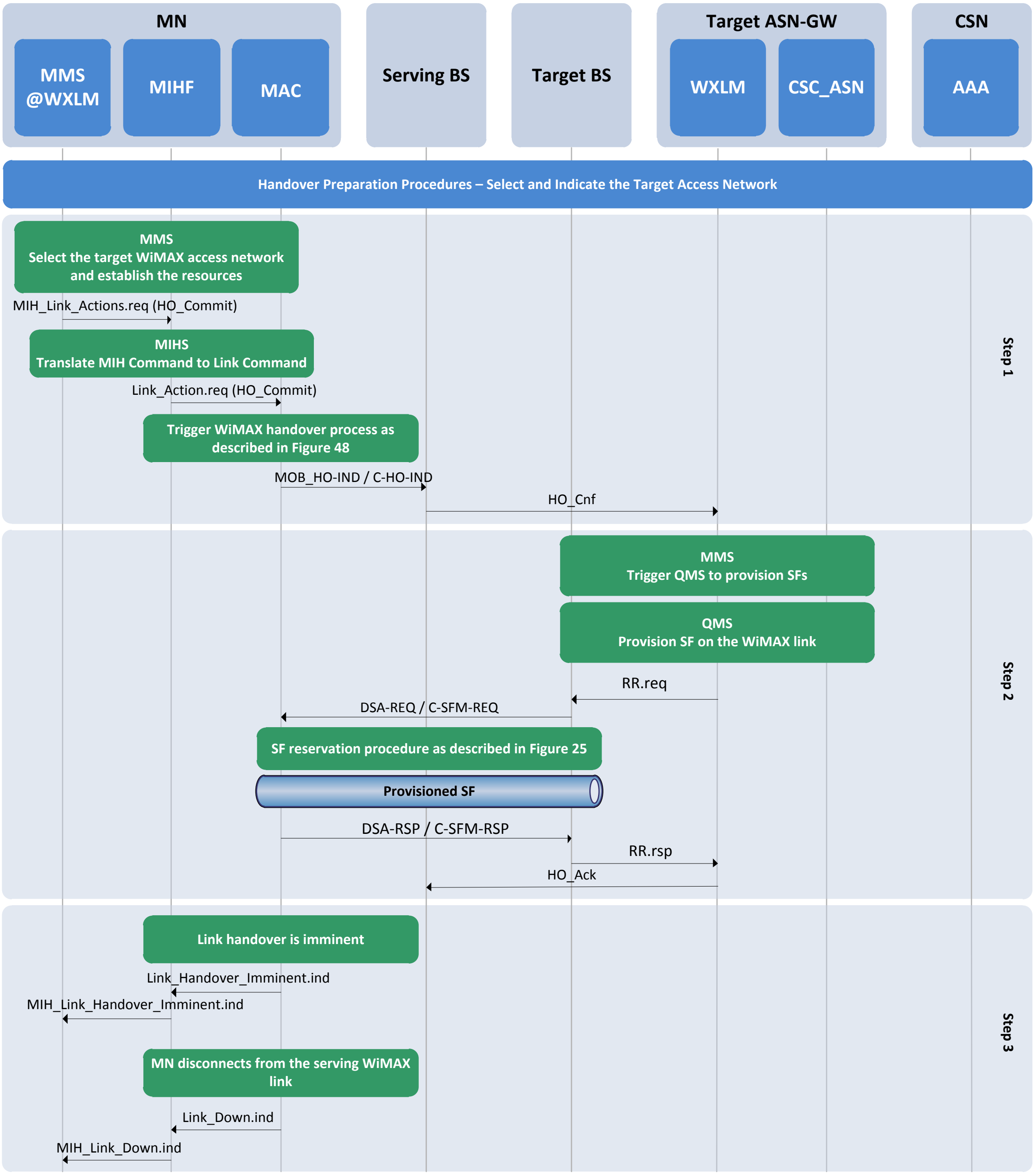

Figure 5-17: WiMAX macro-mobility scenario – network confirmation (handover preparation phase)

5.4.1. Handover Execution Phase

In this phase the handover between the serving and the target BS is executed at both the physical and the IP level. The following internal steps are identified (illustrated in Figure 5-18).

Step 1:

- The MN WiMAX link layer establishes connectivity with the target BS (*RNG-REQ/RSP* MAC management messages);
- As a result, a *Link_Up.ind* event is generated towards the MMS at the MN.

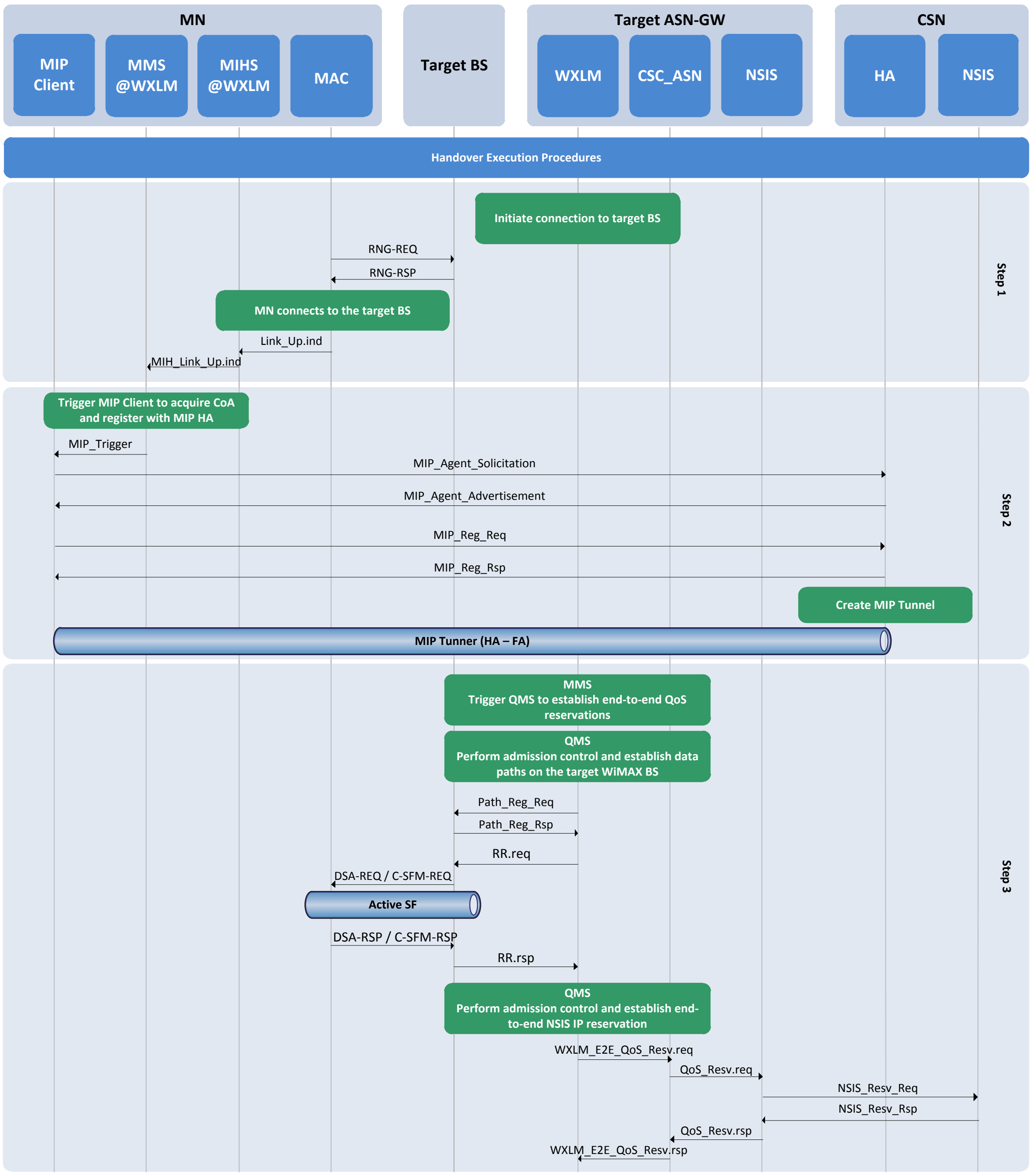

Figure 5-18: WiMAX macro-mobility scenario – handover execution phase

Step 2:

- The MMS at the MN triggers the MIP client on the MN to solicit an Care-of-Address (CoA) (*MIH_Agent_Solicitation/Advertisement* messages) and to register the CoA in the MIP HA (*MIP_Registration_Req/Rsp* messages);
- Consequently, a MIP tunnel between the HA and the FA is created.

Step 3:

- The MMS on the target ASN-GW triggers the QMS to establish the required QoS reservations on the WiMAX air link, WiMAX wireline link between the BS and the ASN-GW (WiMAX Forum *Path_Reg_Req/Rsp* messages), and the E2E QoS reservation (*WXLM_E2E_QoS_Resv.req/rsp* and *NSIS_Resv_Req/Rsp* messages).

5.4.2. Handover Completion Phase

In the handover completion phase, the resources allocated on the previous WiMAX AN are released. The MMS at the new serving ASN-GW triggers a WiMAX Forum *HO_Cmp* message towards the previous ASN-GW. The MMS at the previous ASN-GW triggers the QMS to release the allocated SFs on the WiMAX link (*DSD-REQ/RSP* MAC management messages).

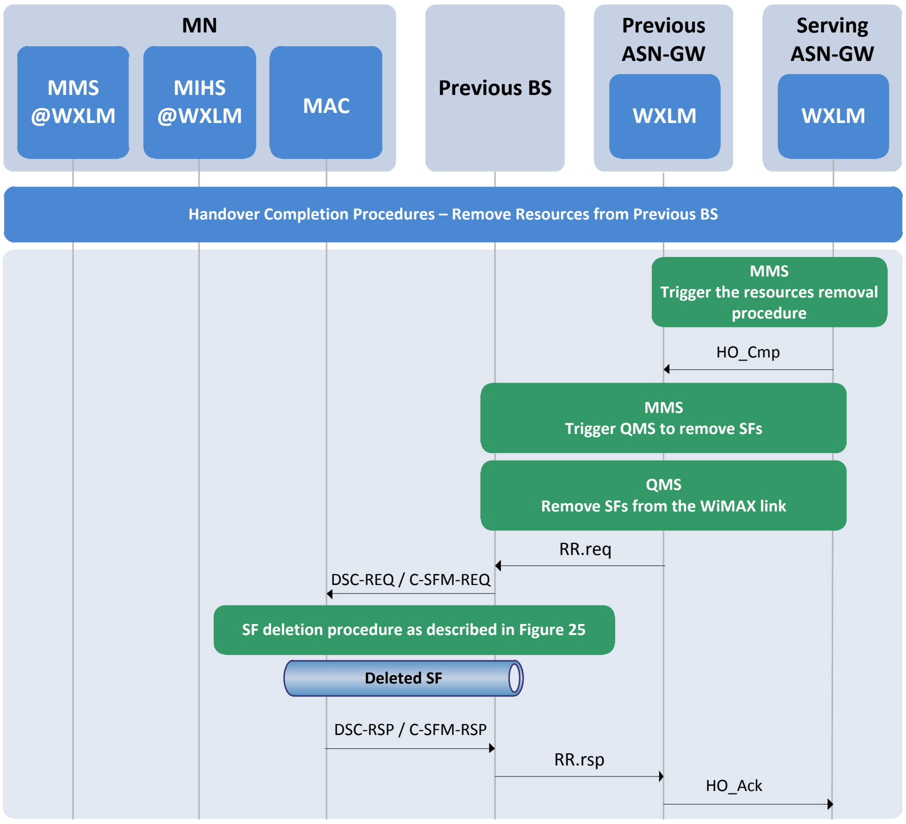

Figure 5-19: WiMAX macro-mobility scenario – handover completion phase

5.5. Experimental WiMAX Macro Mobility Scenario

This section introduces the experimental scenario developed to obtain performance measurements related with the proposed mobility enhancements [180] [181]. Furthermore, it is also presented the required modifications to the WiMAX mobility architecture to accommodate the deployed scenario.

5.5.1. Scenario Description

Up to now we have described the mobility and QoS architecture modules and their operation. In the following paragraphs we will present a practical use case of a WiMAX handover in the backhaul link. In the last mile, the scenario presents an inter-technology handover between Ethernet and Wi-Fi demonstrating efficient management of control plane functionalities, as well as data plane configuration and QoS resources reservation. The example scenario is shown in Figure 5-20. It consists of a MN with two network interfaces (Ethernet and Wi-Fi), initially connected to an Ethernet cable, backhauled by a WiMAX fixed Subscriber Station (SS) (serving SS). Later on, the user decides to move away from his desk and unplugs the Ethernet cable. Consequently, the MN connects to the Wi-Fi network, backhauled by another WiMAX fixed SS (target SS), located in the same ASN of the serving SS. This type of scenario includes inter- and intra-technology mobility procedures: the MN is connected via Ethernet and makes an inter-technology handover to a Wi-Fi network; at the same time, there is an intra-technology handover from the serving WiMAX SS to the target WiMAX SS in the backhaul, following the intra-ASN WiMAX mobility model.

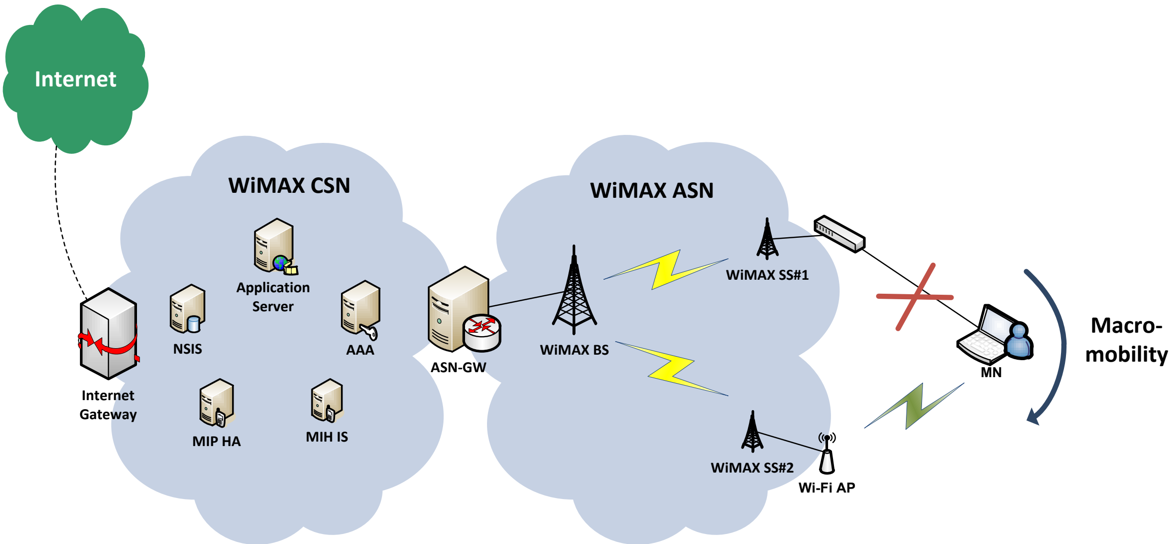

Figure 5-20: Experimental WiMAX macro-mobility scenario

In our prototype, some applications are running on the laptop while it is connected via the Ethernet segment. The corresponding sessions are activated with the associated resources reserved along the end-to-end path. In particular, a set of WiMAX SFs is activated between the serving SS and the associated BS during the session setup phase when the applications is initialized. Each current SF is characterized by the WiMAX parameters and the scheduling class more suitable for the QoS requirements of the active services. When the user moves to the Wi-Fi network, the same QoS level must be assured for each running application, so new SF must be created and activated in the WiMAX segment between the target SS and the associated BS.

This mobility scenario includes both intra-technology and inter-technology handover: the inter-technology handover involves the Ethernet and the Wi-Fi technology, but since they are backhauled by two different WiMAX SS when the MN moves, an intra-technology handover from the serving WiMAX SS to the target WiMAX SS must be performed.

5.5.2. Architecture Overview

In order to implement the scenario depicted in Figure 5-20, it is necessary to adapt the proposed WiMAX mobility architecture, described in Figure 5-3, on the MN side. Since the MN is connected to the Wi-Fi and Ethernet access technologies, instead of the WiMAX access interface, some adaptations are required on the MN architecture. Shortly, it is necessary to specify and implement an entity responsible for managing, interfacing and controlling the new access interfaces of the MN (Wi-Fi and Ethernet). To achieve this aim the Link Layer Controller (LLC) is specified and integrated with the remaining modules of the MN, as illustrated in Figure 5-21.

The LLC is the software module located on the MN that is in charge of monitoring the state of the local network interfaces (Ethernet and Wi-Fi) and interacts with the WXLM MIHS in order to trigger the resources reservation on the new WiMAX segment when a handover procedure is necessary.

The communication between LLC and MIHS is compliant with the IEEE 802.21 MIH_LINK_SAP that specifies an abstract media independent interface between the MIHF and the lower layers media-specific protocol stacks such as IEEE 802.3 (Ethernet) and IEEE 802.11 (Wi-Fi).

The primitives exchanged between LLC and MIHF are the following:

- *Link_Up*: this event is sent by the LLC to notify that a link layer interface is configured and ready to be used;
- *Link_Going_Down*: this event is sent by the LLC to notify that an AN interface is expected to go down within a certain period. In the implemented scenario, this event is used to trigger the resources reservation on the new WiMAX segment;
- *Link_Down*: this event is sent by the LLC to notify that an AN interface is broken. In the implemented scenario, this event is used to trigger the handover process and delete the QoS reservation on the previous WiMAX segment;
- *Link_Action*: this command is sent by the MIHF to perform an action on a pre-defined link layer connection. In the demonstration environment, it is used by the LLC to notify the user that the resource reservation on the new WiMAX channel is completed.

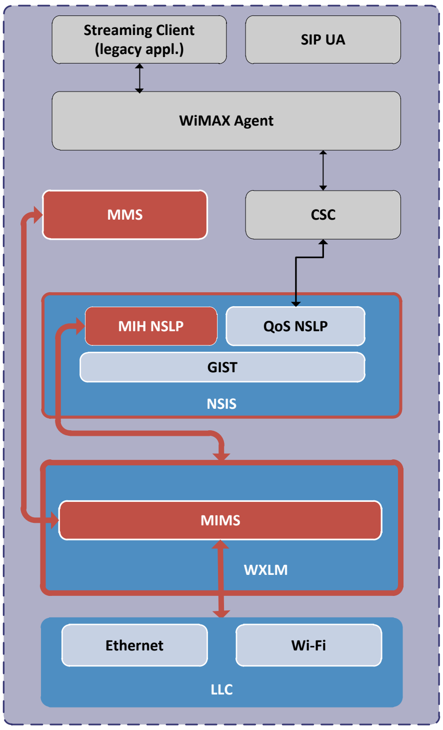

Figure 5-21: MN architecture – link layer controller

The LLC is endowed with a GUI that allows the user of the MN to know the networks connectivity state. When the state of a network interface changes, the color in the circle depicted in the GUI varies and a new message appears in the text area to notify the user of the event. Therefore, he can evaluate the situation and take a decision. For example, if both the Ethernet and Wi-Fi interfaces are ready to be used, the user can trigger the *Link_Going_Down* event by pushing the button on the GUI.

Moreover the GUI is also employed to allow the user to know the result of the resource reservation procedure on the new WiMAX channel. An internal timer is started when the LLC sends the *Link_Going_Down* event to the MIHF. If the *Link_Action* command is received before the timeout, the QoS reservation is considered successfully completed and a message is shown on the GUI. Otherwise, the QoS reservation fails.

5.5.3. Handover Signaling Description Overview

Figure 5-22 presents the macro-mobility signaling diagram applied to legacy applications, characterized by host-initiated sessions, for the scenario described in section 5.5.1.

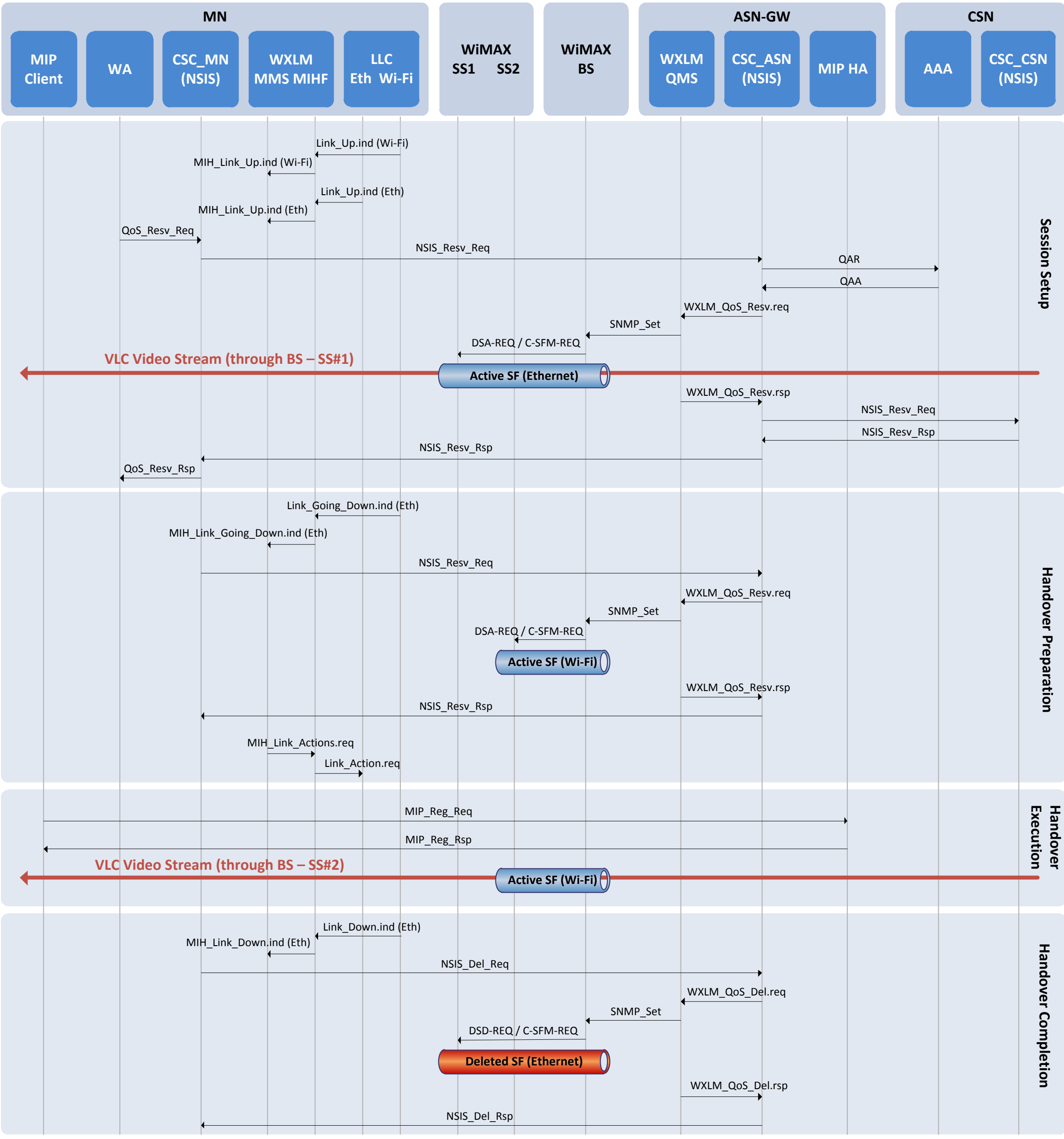

Figure 5-22: Experimental scenario – WiMAX handover signaling description

In the first phase, named session setup, after the MN attachment, two MIH *Link_Up* events are sent by the LLC to notify the MIHS that Wi-Fi and Ethernet networks are available. The MIHS forwards these events to the registered MMSs (local and remote through the MIH protocol), which will update their internal state machine. When the user starts a legacy application, the resource reservation procedure is triggered by the WA and the end-to-end QoS NSIS signaling is initiated. As a result, a set of WiMAX SFs are created by the WXLM between SS#1 and the BS in order to assure the required QoS. Note that this process still involves the user authentication through AAA, and the QoS reservation at the ASN-CSN link, if the required application is located in the CSN side.

Thereafter, in the handover preparation phase, the user interacts with the LLC in order to notify that it wants to abandon the serving WiMAX link (connected to the Ethernet cable). As a result, the LLC sends a *Link_Going_Down* event to the MIHS that forwards it to the registered MMSs. The MMS internal state machine is updated again, and the resources reservation in the target link is triggered before the Ethernet cable is unplugged. The MMS selects the target WiMAX SS#2, connected to the Wi-Fi link, as the target network for the handover and notifies this decision to the CSC_MN, which will trigger a new NSIS QoS signaling to update the resource reservation for the existing sessions and create new SFs in the target segment. The NSIS response message notifies the CSC at the MN that resources have been allocated between the target SS#2 and the BS and that they can be used by the data traffic flows after the handover. When this reservation is done, the MMS sends a *Link_Action* command to the LLC, notifying the later that the MN can move from the home network to the foreign network maintaining the same QoS level originally required by the active applications.

During the handover execution phase the user unplugs the Ethernet cable from the MN, the Wi-Fi network interface starts the MIP registration procedures with the FA, and the MIP tunnel between the FA and the HA at the ASN is established. Data traffic is carried through the Wi-Fi link and is mapped to the new WiMAX SFs between the target SS and BS on the WiMAX link, assuring the QoS level originally required by the active applications.

The resources, previously allocated between SS#1 and BS, are released during the handover completion phase. When the Ethernet cable is unplugged, the LLC sends a *Link_Down* event, forwarded by the MIHS to the MMS. Thereafter the CSC_MS triggers the deletion of the previous WiMAX SFs for the existing sessions. The whole process finishes in the session conclusion phase, in which, after the application is terminated, the WA triggers the deletion of the end-to-end QoS that was originally requested (not only in the WiMAX link, but also in the ASN-CSN link, if needed).

5.6. Experimental Performance Evaluation

This section presents a set of experimental performance measurements for WiMAX macro mobility scenarios enhanced with IEEE 802.21 functionalities. Section 5.6.1 provides signaling measurements for the handover procedure, whereas section 5.6.2 presents QoS measurements during the handover procedure.

5.6.1. WXLM Handover Signaling Measurements

This section presents the obtained signaling results in the testbed. Internal processing times of several modules involved during the different handover phases are analyzed, as well as a performance evaluation of the MIH transport protocol for the communication between peer IEEE 802.21 entities.

5.6.1.1. Implemented Demonstrator and Tests Methodology

This section describes the empirical evaluation of the proposed mobility management architecture prototype. The experimental scenario was depicted in Figure 5-20. The testbed includes modules that implement the CSN, ASN and MN functionalities. Under the ASN, a real, commercial-of-the-shelf (COTS) WiMAX BS is directly connected to the ASN-GW. Two WiMAX SSs are connected to the BS creating a Point-to-Multipoint topology. The MN is connected to SS#1 by Ethernet and to SS2 by Wi-Fi. The video server is located in the CSN and the video client in the MN. To carry out the handover between Ethernet and Wi-Fi, the MIPv4 mobility management protocol is used. Table 5-4 summarizes the testbed components.

The goal of this testbed is to evaluate the effectiveness of WiMAX technology in a mobility scenario (handover between Ethernet and Wi-Fi, backhauled by WiMAX), regarding QoS reservation in WiMAX links and user's authentication mechanisms. Initially the MN is connected to Ethernet and therefore it is necessary to reserve, in the BS – SS#1 WiMAX link, two Service Flows (one uplink and one downlink), with an allocated bandwidth of 512 Kbps, to handle a video stream. While the user is watching a video received through the concatenated WiMAX/Ethernet link, he decides to unplug the Ethernet cable and connect to the Wi-Fi network. This automatically triggers a handover procedure between Ethernet and Wi-Fi, which will initiate the SFs reservation in the BS – SS#2 WiMAX link. After this process, the user performs the handover and can continue to watch the video through the composed WiMAX/Wi-Fi link, experiencing the same video-quality.

Table 5-4: Testbed components

Equipment	Field	Value
Base Station and Subscriber Stations (RedMAX)	Frequency Band	3.5 GHz
	Channel Bandwidth	7 MHz
	PHY WiMAX	802.16d, OFDM
	Downlink Ratio	56/44
	Uplink and Downlink Modulation	64 QAM ¾
	BS and SS Distances	15 m
Servers	Ubuntu 8.04 (Linux)	
MNs	Ubuntu 8.04 (Linux)	

A brief summary of the WEIRD modules involved in the scenario and their main functionalities is provided in Table 5-5.

Table 5-5: Architecture modules

Module	Description
VLC Client & Server	Application
CSC_MN	Connectivity server controller located on the MN
Link Layer Controller (LLC)	Monitoring the state of the MN network interfaces
WiMAX Agent (WA)	Resource reservation provisioning for legacy applications
MIHF	MIH Function (part of 802.21 architecture)
NSIS Framework	NSIS QoS signaling
WXLM	Service flow management / Admission control / Resource reservation control /
AAA Server	Authentication, authorization and accounting
Administration Console	Control plane monitoring
CSC_ASN	Connectivity service controller located on the ASN-GW
CSC_CSN	Connectivity service controller located on the CSN
MIP (Home Agent, Foreign Agent)	Agents enabling the Mobile IP protocol

This scenario evaluates the performance of real-time applications, when there are QoS and mobility signaling operations, with and without load in the WiMAX links. The content of the application (which lasted 60 seconds) is an IPTV stream, which includes a variable bit rate video stream of 512 Kbps (360×288, 25 f/s), and a constant bit rate audio stream of 192 Kbps. In addition, the application content is composed by a VoIP call with an effective application bitrate of 17.6 Kbps. To generate load in the WiMAX links, a different number of VoIP calls in background were emulated, starting with 0 and ending with 120, with incremental units of 20 users. The absence of background traffic is mainly to isolate the performance of the individual modules, without any external disturbing. The aim is to assess the performance of a VoIP client in an operator perspective. Thus, the service provided to a single client is evaluated considering the concurrency of other identical clients (from 20 to 120). All the application and background traffic are emulated with JTG, which allows an accurate sending and processing of streams in a network using senders and receivers nodes. Different SFs are configured: one for the applications triggered by the WA, as explained before, with a required bandwidth of 100 Kbps – 1 Mbps and a real time Polling Service (rtPS) scheduling service; other for background VoIP calls and signaling, which has less priority (Best Effort) than the application SF. It is used PTPd framework to achieve synchronization in our testbed: the offset between the different host clocks was lower than 100 µs, after waiting the necessary time for achieving synchronization. For each number of VoIP calls in background, each run was repeated 10 times, which is feasible in a real-testbed environment.

The measurements are based on a NSIS evaluation framework and on enhancements in the proper modules. The NSIS evaluation framework collects measures from NSIS nodes (QoS-NSLP, GIST, MIH-NSLP) and performs the respective calculations, for instance, message association setup time and internal message processing. Moreover, the enhancements on the diverse modules include time-measurements on start and end events. For instance, the *Link_Up* event is delivered to the MMS entities on the MN and on the ASN-GW, thus it is possible to measure the MIH transport protocol performance.

5.6.1.2. Results

As discussed in section 5.5.3, the handover process follows the make-before-break model and consists of three main sequential phases: handover preparation, execution and conclusion. The first step includes all the procedures to configure the target segment, while during the handover execution the data path towards the foreign network is established. Finally, existing resources on the old path are removed during the handover conclusion phase.

In order to assure the same level of QoS for the active applications when the user moves to the foreign network, the configuration of the target resources during the handover preparation requires the coordination between the entities handling mobility and session control, as well as the exchange of NSIS messages between the MN and the ASN for the creation of new SFs. Similar procedures were adopted during the handover conclusion to delete the old resources. The resource reconfiguration phase (handover preparation), based on IEEE 802.21 framework, provides QoS-aware mobility and does not have impact on the overall handover procedure. The handover execution phase is based on MIPv4 and includes the creation of the MIP tunnel between the FA and the HA located in the ASN-GW.

5.6.1.2.1 Session Setup

QoS signaling related with the session setup phase involves the creation of the application dedicated SF and is depicted in Figure 5-23. The modules introducing higher delay correspond to NSIS, as the association mechanisms of GIST are highly influenced by the background traffic. Regarding the processing time of CSC_ASN and related modules, which involves the user authentication through communication with the AAA, and the resources reservation in SS#1 through the WXLM, it is almost stable, even with an increasing number of background VoIP flows: its value of nearly 1 – 1.5 seconds is mostly due to the authentication process. The reservation of QoS in the ASN-CSN link has a very small value in the overall process.

As soon as the *Link_Going_Down* event is generated at the MN, the MMS, in cooperation with the CSC_MN, initiates all the signaling process to reserve resources in SS#2. Such processing includes the creation of a SF in SS#2, assisted by all the modules responsible to manage QoS, namely the NSIS framework. Since the default service flow gets overloaded by the background traffic (120 simultaneous clients), the processing time of these modules increases exponentially. Moreover, the CSC_ASN and the WXLM services also participate in the QoS chain, which maintain their performance values while increasing the background traffic, since these modules do not hold transport functionalities as the NSIS framework.

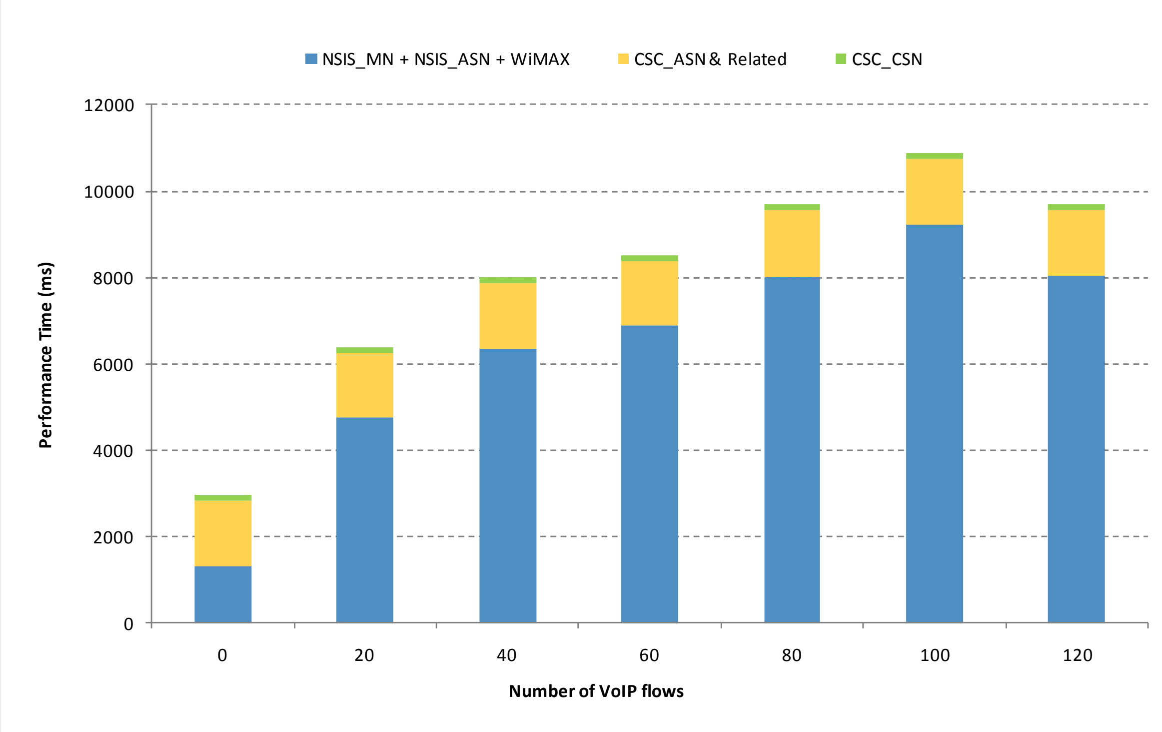

Figure 5-23: Session setup phase measurements

5.6.1.2.2 Handover Preparation Phase

Figure 5-24 depicts the values of the second phase – handover preparation phase.

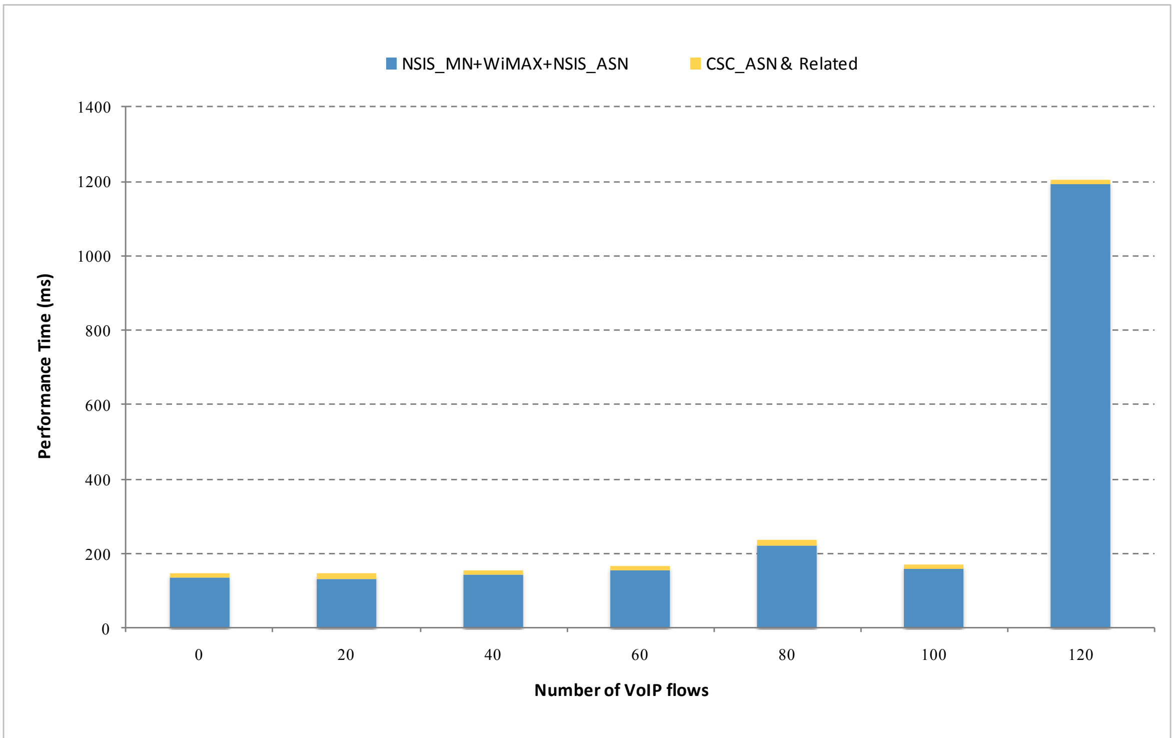

Figure 5-24: Handover preparation phase measurements

5.6.1.2.3 *Handover Execution Phase*

The employed version of Mobile IP, which has interference in the handover execution phase, relies on MIPv4. The HA is configured on the WiMAX ASN and the FA is configured in a dedicated machine of the foreign network. While the MN is at the home network, it receives advertisements from the HA, configured with a lifetime of 3 seconds. These advertisements are sent on a second basis, although such interval can be reduced in an updated version of MIPv4. During the handover, the MN loses its connection to the HA and detects a new link via the agent advertisements sent by the FA. As the registration is required (R-flag), the MN sends a *Registration_Request* message to the FA, which processes the request and then relays it to the HA. The HA replies to the FA, granting the request, and on its turn the FA processes the Registration Reply and relays it to the MN. The delay introduced by MIP processing is very low (around 30ms). The main issue with the used MIPv4 version is that the advertisement lifetime takes, at least 3 seconds to expire, thus, only after this period the MN starts using the new prefix. Such feature has a direct consequence in packet loss, the above-mentioned 7%.

5.6.1.2.4 *Handover Completion Phase*

The handover completion phase, triggered by the *Link_Down* event, does not depend on the number of VoIP flows. The processing of the CSC_ASN and related modules is almost invariable. In terms of complexity, the handover completion is simpler than the preparation as it only involves deletion of resources. This way, the signaling messages have a lower size, being less prone to influences by background traffic, when compared to the first phase – the creation process.

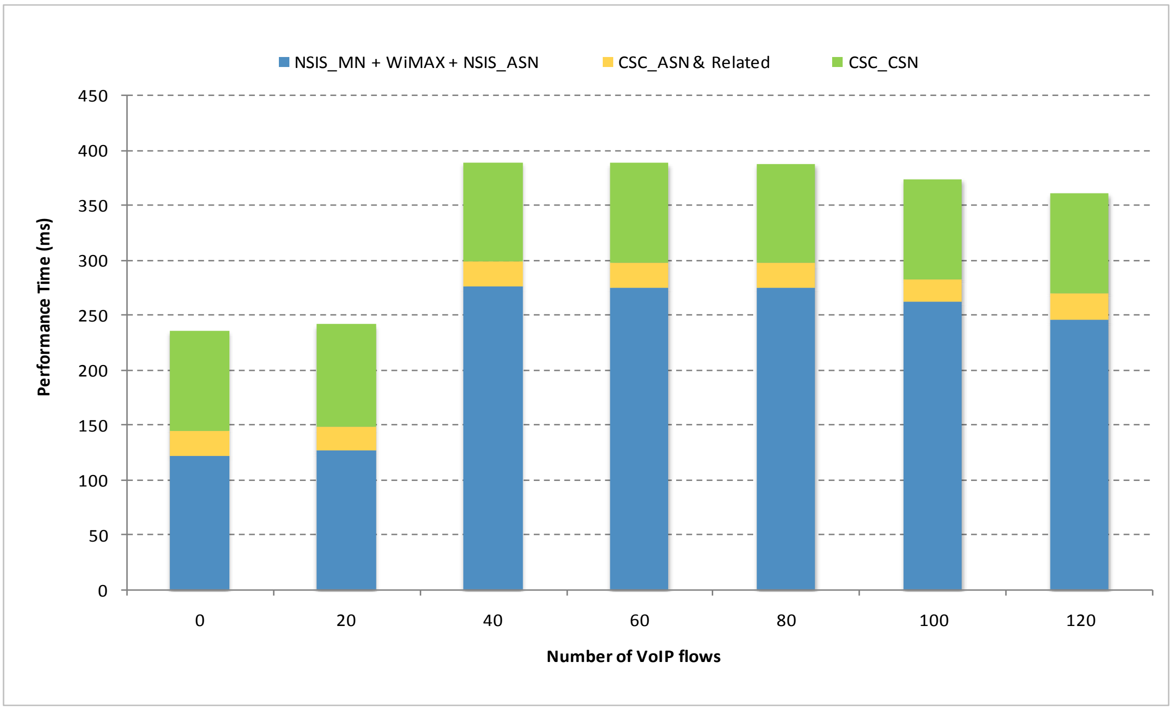

Figure 5-25: Handover completion phase measurements

The final phase – handover completion phase, corresponding to the deletion of the application flow, is depicted in Figure 5-25. The NSIS framework introduces larger values of delay, due to the propagation of signaling in the background flow.

5.6.1.2.5 *MIH Transport Protocol*

The MIH signaling includes the processing of MIH events and their respective transport. Figure 5-26 depicts the total processing time for modules involved in the MIH events transport. Such modules include GIST and MIH NSLP; moreover, the transfer time in WiMAX and Wi-Fi is also considered.

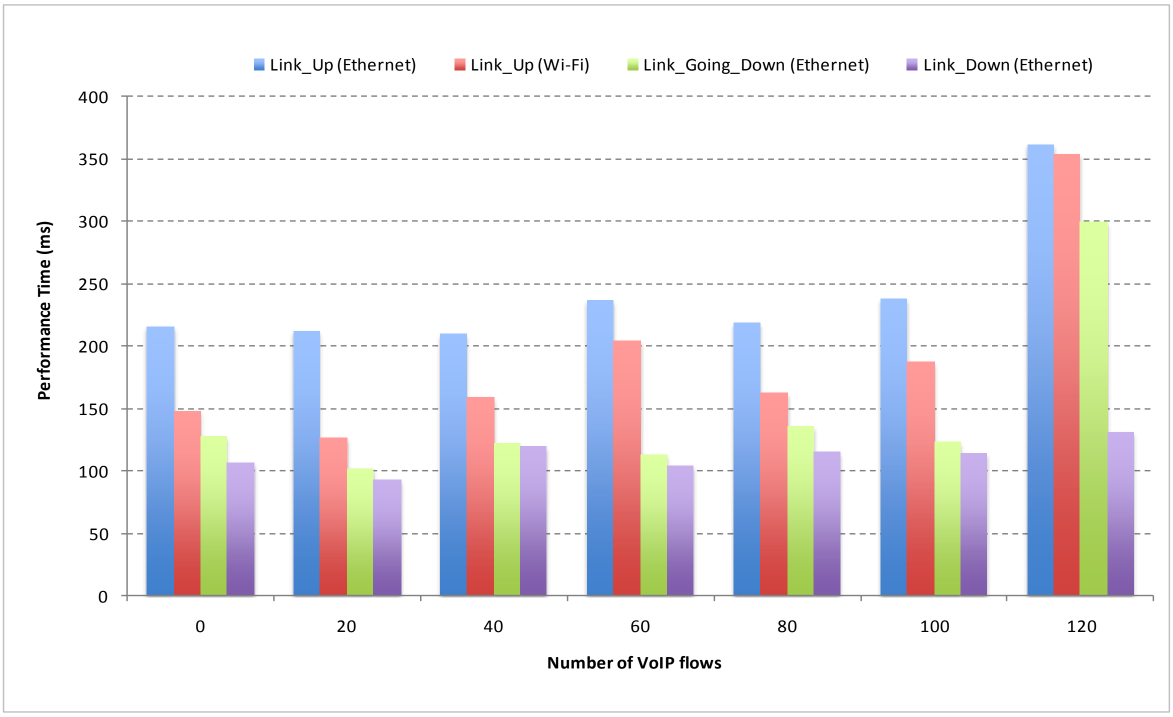

Figure 5-26: NSIS MIH transport measurements

GIST, as a transport protocol for the MIH messages, has a decreasing performance with the number of background traffic. As GIST exchanges several messages to establish the association between peers, the performance of the network directly impacts this GIST operation. The Association is established on the session initiation, which corresponds to the *Link_Up* event. This event, as the first one being propagated, requires the GIST association between MN and ASN nodes. Moreover, the *Link_Up* is the second event to be generated and consequently to be propagated. As it is sent almost at the same time of the Ethernet *Link_Up* event, the Wi-Fi *Link_Up* is only propagated when the association procedures initiated by *Link_Up* event are concluded. The *Link_Going_Down* and *Link_Down* events have similar performance, as they are propagated after association completion. In addition, the *Link_Down* event has better performance as the tear down of resources are much simpler than the creation or updates in the GIST protocols.

MIH-NSLP is a module in the MIH signaling that parses the MIH messages, maps the IP address to the MIH identifier of the MIHF destination, and serializes the Message Routing Information (MRI) object to instruct GIST delivery process. The performance of this module is slightly affected with the increasing load. At the MN, the MRI serialization process takes around 9 ms, while the processing associated to MIH messages and interfacing with GIST, takes around 12 ms with no background traffic, and 20 ms with 120 simultaneous clients in the default SF. At the ASN side, the reception processing remains in the range of 8 to 9 ms, with no meaningful variations for the cases with or without load. It is also relevant to point out that the propagation time of different messages in WiMAX is approximately 30 ms. Such delay influences GIST performance, thus message association setup processing time includes the internal processing of GIST and the WiMAX propagation delay.

The possibility of creating dynamic reservations and the adaptation to mobility introduces benefits to applications. In the first phase performance decreases, since the session setup modules participating in the signaling chain have a high impact. The remaining phases have an acceptable performance, which is mainly affected by the increased number of simultaneous flows. For instance, with a load higher than 100 VoIP flows, the achieved performance of modules is not within acceptable bounds (delay with values around 1s, which is not acceptable for VoIP, if we consider 150ms as the acceptable one-way delay).

5.6.2. WXLM Handover QoS Measurements

This section presents the QoS results obtained in the testbed. The applications' jitter, throughput, packet loss and one-way delay were measured, before and after the handover.

5.6.2.1. Implemented Demonstrator and Tests Methodology

Herein it is measured the application's QoS before and after the handover, that is, when the applications traffic is flowing between the traffic source in the CSN and the MN, through the WiMAX link between the BS and the serving SS (before the handover), and then, through the WiMAX link between the BS and the target SS (after the handover).

5.6.2.2. Results

5.6.2.2.1 Packet Loss

During the handover execution phase, the MN does not receive application packets. The communication is interrupted, mostly because of Mobile IP framework, which is used in this testbed to manage the IP handover process. The communication break causes a packet loss of approximately 7%. When the MN is properly connected to the Eth/WiMAX link (before the handover) and Wi-Fi/WiMAX (after the handover), the packet loss values are always close to 0%, even with an increase in the number of background VoIP calls, since audio and video streams are the most priority traffic.

5.6.2.2.2 Packet Jitter

Applications' jitter is always approximately 26 ms for audio, 20 ms for the VoIP call, and 18 – 19 ms for video (after and before the handover). These results demonstrate that audio is the real time traffic that can achieve transmission rates closer to the theoretical rate (it is more adjusted at the physical level), and the jitter values does not depend on the saturation of WiMAX links.

5.6.2.2.3 One-way Delay

The one-way delay, illustrated in Figure 5-27, for the different applications is approximately the same for all the cases with variable numbers of background flows. They are always nearly 10 ms, increasing slowly when the WiMAX links are not saturated. However, audio and video applications suffer an increase in the delay when the number of background VoIP calls completely saturates the WiMAX channels (e.g., the case of 120 VoIP calls).

5.6.2.2.4 Packet Throughput

Finally, as depicted in Figure 5-28, all applications' throughput is extremely close to the theoretical value (512 Kbps for video, 192 Kbps for audio and 17.6 Kbps for VoIP). However, they slightly decrease when the WiMAX links starts to saturate, even for the high priority applications. It is also shown that the throughput before the handover is higher than the one after handover, mostly due to the shift from the Ethernet link to the Wi-Fi link.

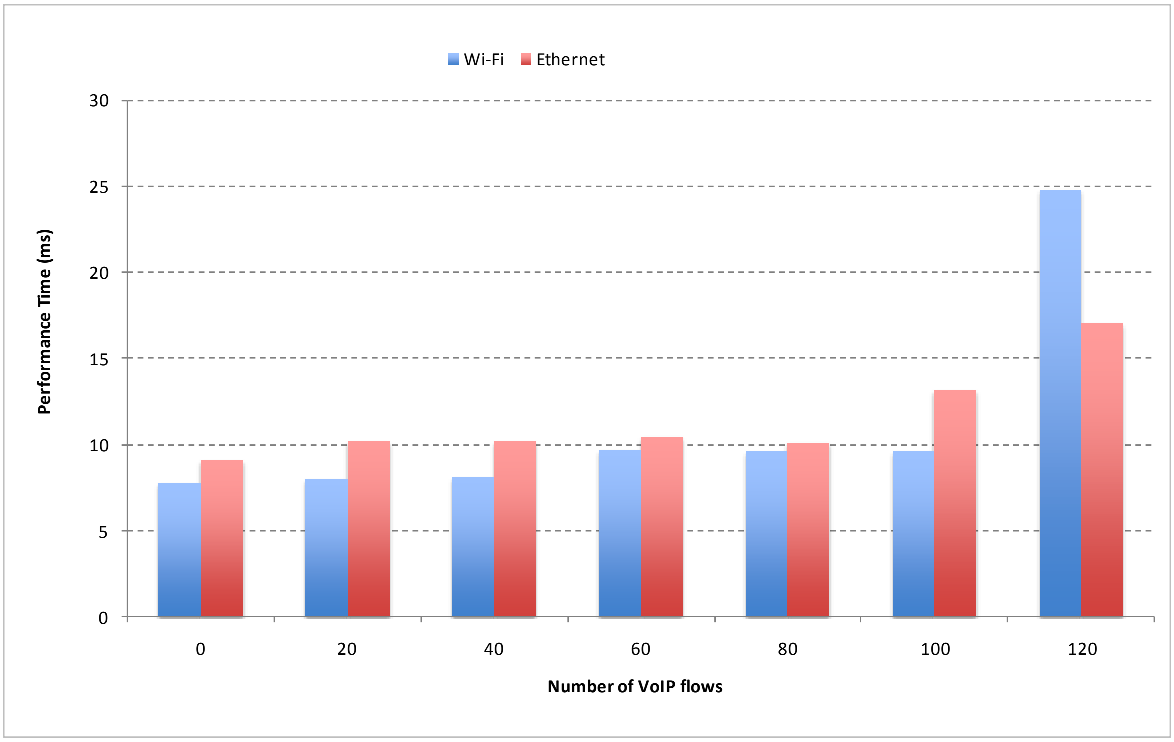

Figure 5-27: Measured one-way delay for VoIP

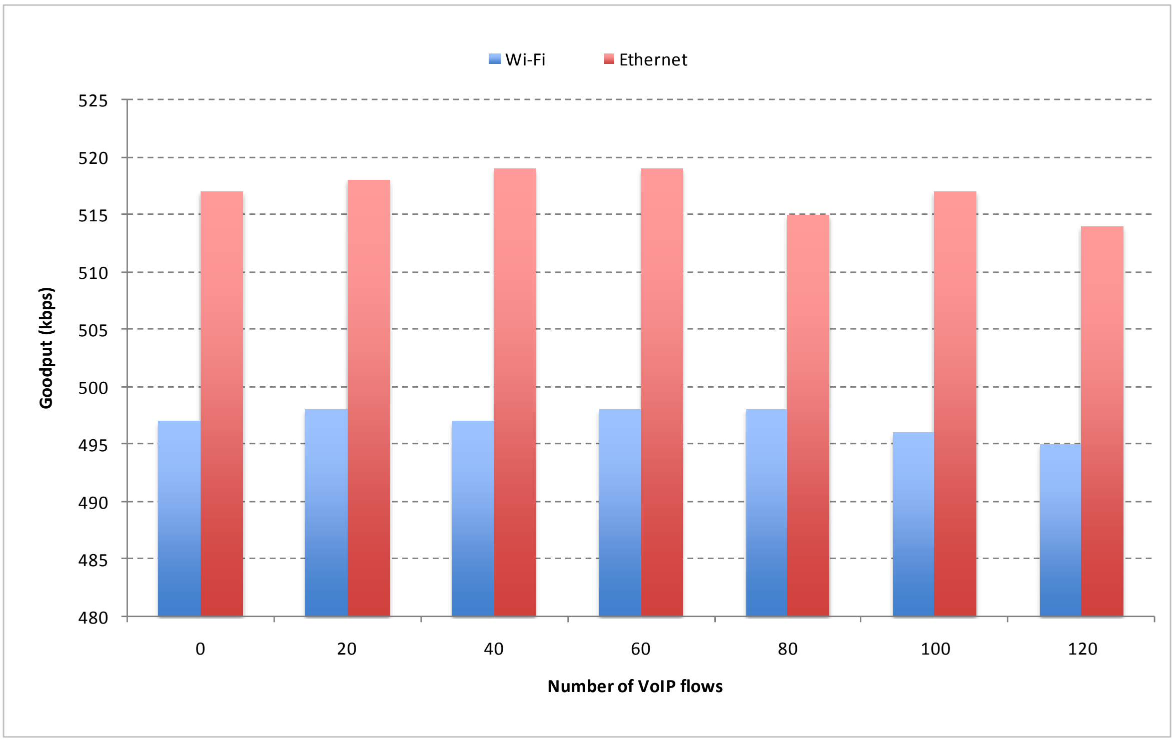

Figure 5-28: Measured throughput for video

5.7. Summary

Given the user requirements for next generation applications, handover mechanisms must be developed while maintaining adequate levels of QoS. This chapter has presented a solution that addresses this twofold problem based on a QoS-enabled architecture for mobility management in WiMAX networks.

This chapter described a WiMAX architecture based on IEEE 802.21, which integrates mobility and QoS mechanisms. The proposed architecture enhances the mobility mechanisms in WiMAX ANs and is appropriate to address scenarios with real-time applications. The architecture integrates QoS functionalities, specifying mechanisms to enable the complete combination of mobility and QoS, using an extension of the NSIS protocol with IEEE 802.21 information.

Two WXLM cross-layer services – MIHS and MMS – were proposed to optimize the mobility procedures in WiMAX. The MIHS provides standardized and media independent interfaces, based on the IEEE 802.21 framework, to enable the efficient communication between the upper layers and the WiMAX link. The MMS manages all the handover procedures, including the handover initiation, preparation, decision and completion phases. The MIMS is also extended with support for an 802.21 compliant interface.

Detailed message sequence charts are also presented in this chapter to illustrate the integration of IEEE 802.21 MIH framework with WiMAX mobility procedures. A macro-mobility scenario is presented, with particular focus on the WXLM mobility related services – MMS and the MIHS.

Finally, it is presented a practical use case of a WiMAX handover in the backhaul link. In the last mile, the scenario presents an inter-technology handover between Ethernet and Wi-Fi. This type of scenario includes inter- and intra-technology mobility procedures: the MN is connected via Ethernet and makes an inter-technology handover to a Wi-Fi network; at the same time, there is an intra-technology handover from the serving WiMAX SS to the target WiMAX SS in the backhaul, following the intra-ASN WiMAX mobility model. Shortly, the results indicate that the architecture modules introducing higher delay correspond to the NSIS modules, due to the GIST association mechanisms. Although most of the signaling control timings are approximately constant with the increase in the network load, they increase sharply when the network gets congested. Overall, the handover effect in the application flows is not noticeable, as all the process is prepared beforehand, and QoS is established in the new WiMAX network.

In the following chapter the described architecture is extended to support seamless handover procedures in heterogeneous access networks, such as WiMAX, Wi-Fi and 3GPP.

6. Optimized Fusion of Heterogeneous Wireless Networks based on Media Independent Handover Operations

The proliferation of wireless network technologies has offered consumers the ability to connect to the Internet in many alternative ways. Ubiquitous network access is emerging as the number one target of the industry for the future. It is expected to give a boost to the telecommunications market, improve operators' revenues and provide the new 4G-driven networking paradigm for service provisioning over heterogeneous access technologies.

A major concern in such settings is the cooperation between the diverse networks or, differently stated, how the plethora of available wireless access means, such as Wi-Fi, WiMAX, UMTS and LTE, can inter-operate in order to always offer the best services, everywhere and at any time according to the *Always-Best Connected* (ABC) paradigm.

Although the work within the IEEE 802.21 working group is already in an advanced stage, the framework needs to be integrated with specific access technologies, since each one has its particular type of interfaces and primitives. Moreover, seamless mobility requires the active support of Quality of Service (QoS) related mechanisms in the handover process, guaranteeing that resources are reserved in the Target AN (TAN) before mobility management operations are completed. On top of the WiMAX-oriented architecture defined in chapters 4 and 5, herein is presented an inter-technology seamless mobility architecture with integrated QoS support, based on IEEE 802.21 [185] [186] [187]. The proposed architecture can accommodate different wired and wireless technologies, such as WiMAX, Wi-Fi, UMTS/HSPA and LTE [188] [189] [190].

Under the scope of this Thesis, two main alternatives for implementing the IEEE 802.21 Point of Attachment (PoA) and Point of Service (PoS) entities in a real network environment are proposed and discussed, as well as the mapping and translation of the WiMAX, Wi-Fi and UMTS/HSPA specific primitives to the IEEE 802.21 service primitives. Moreover, the way mobility management processes are intertwined with QoS mechanisms in order to support seamless mobility over heterogeneous networks is also described [191] [192] [193]. In this context, it is also explained a proposal to extend the IEEE 802.21 framework with QoS management capabilities, enabling the resources reservation and deletion during a handover procedure on the Radio Access Technologies (RATs) using IEEE 802.21 [194]. Finally, it is proposed a vertical mobility manager to control the handover process between different wireless access networks and interact with the QoS manager.

This chapter also presents a detailed technology-independent handover procedure through message sequence charts, supporting both Network and Mobile Initiated Handovers (NIHO and MIHO) and the interactions with the link layer access technologies, presenting a detailed mapping between the media independent IEEE 802.21 primitives and the RATs (WiMAX, Wi-Fi and UMTS/HSPA) specific procedures and interfaces [192] [193].

Finally, we present a prototype implementation [195] [196] of the proposed architecture and provide results from its empirical evaluation on a state-of-the-art testbed using Commercial Off The Shelf (COTS) WiMAX, Wi-Fi and UMTS/HSPA equipments [197] [198]. Using a real-life public demonstrator [198] [199] [200], it was measured the processing time for each module involved in the handover process and the obtained results discussed [197] [200] [201]. Moreover, to complement the prototype evaluation implementation and results, simulations were also developed to evaluate the performance of the proposed architecture in a large-scale environment.

This chapter is organized as follows. Section 6.1 presents the inter-technology mobility architecture based on IEEE 802.21, discussing alternative implementations for the IEEE 802.21 PoA and PoS entities. Section 6.2 introduces the proposed IEEE 802.21 radio resource management primitives, whereas section 6.3 provides a complete inter-technology seamless handover procedure. Section 6.4 presents the integration between the IEEE 802.21 primitives and the WiMAX, Wi-Fi and UMTS/HSPA RATs. Section 6.5 presents and discusses the simulation results for the inter-technology handover procedures in large-scale environments, whereas section 6.6 presents an evaluation of the inter-technology handover procedures in a public operator network with an Android smartphone [202] [203]. Finally, section 6.7 concludes this chapter with a brief summary of the main topics discussed.

6.1. Mobility Heterogeneous Wireless Network Architecture

The proposed mobility heterogeneous scenarios and architecture, comprising Wi-Fi, WiMAX, UMTS/HSPA and LTE ANs, are illustrated in Figure 6-1 and Figure 6-2, respectively. Each AN is composed by the PoA, which provides radio connectivity with the multi-mode Mobile Node (MN), as well as by the Access Network Gateway (AN-GW), which controls the PoAs operation and establishes connectivity with the operator Core Network (CN) entities. The list of PoAs and AN-GWs depicted in the figure are identified in Table 6-1, as defined by the respective standardization bodies.

The several ANs illustrated in the figure are connected to the operator CN in order to offer IP connectivity between an Application Server (AS) in the Internet and a MIH-enabled MN. The architecture supports mobility procedures through Mobile IP (MIP), and is further expanded to support IEEE 802.21 services. Handover decisions are made by the Network Mobility Manager (NMM) and/or the Terminal Mobility Manager (TMM) entities, which directly interact with the mobility management protocol (e.g. MIP) to enforce mobility decisions. By incorporating optimized handover functionalities through IEEE 802.21, a MN has the potential to perform seamless handovers between heterogeneous access systems. Among other important features, the optimized handover framework is able to support:

- MNs capable of operating multiple network interfaces in parallel;
- Network-initiated and terminal-initiated handovers (NIHO and MIHO);
- Optimal handover decisions based on the surrounding ANs and their available resources;
- Radio resources preparation in the TAN before the handover execution – one of the most important characteristics to obtain a *make-before-break* handover procedure;
- Minimum service disruption after handover execution;
- Radio resources removal in the Previous AN (PAN) after the handover execution.

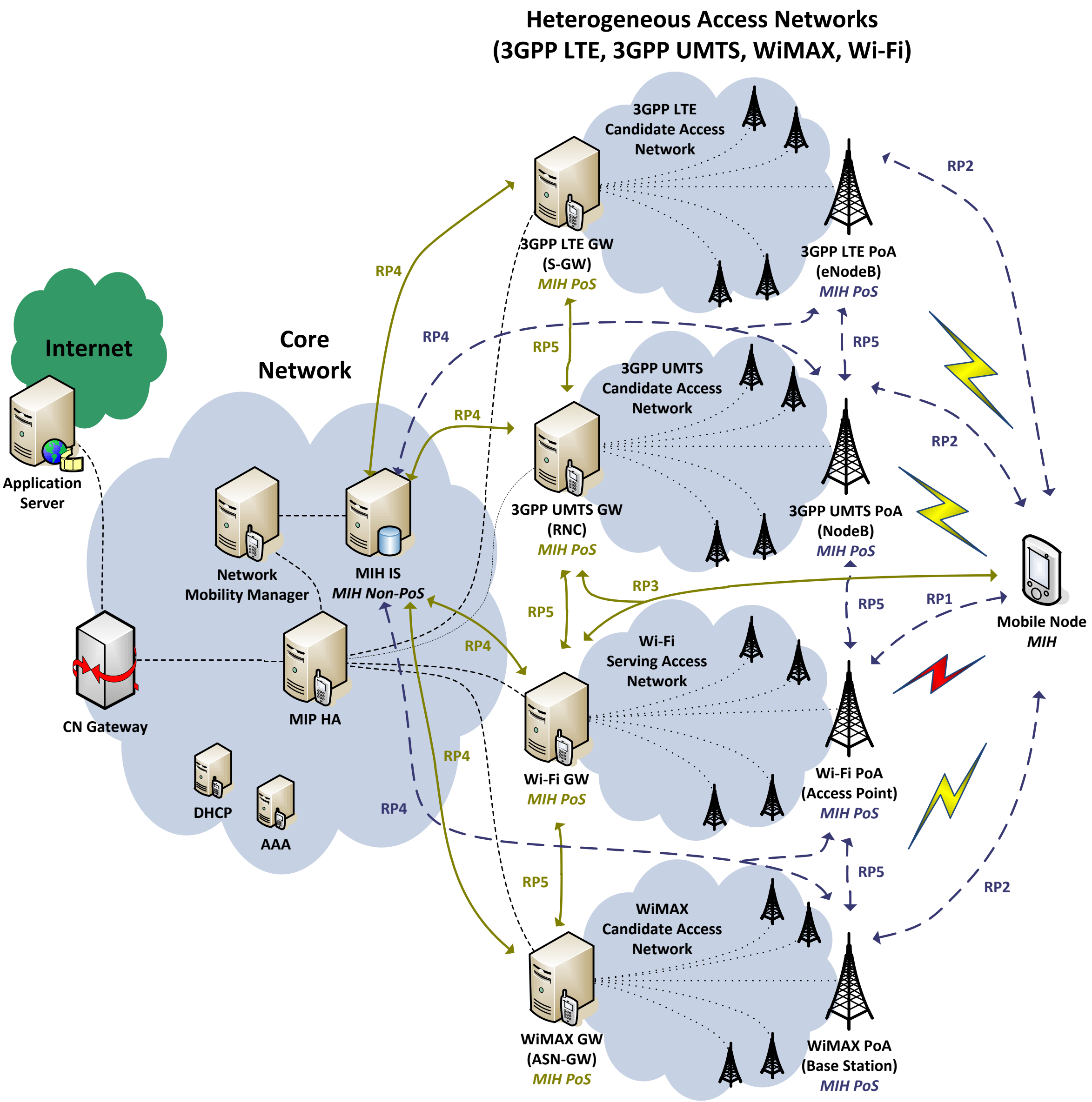

Figure 6-1: Mobility heterogeneous wireless network scenarios

Figure 6-2 depicts the inter-technology mobility architecture components that have been described above. The presented architecture was developed within the framework of the European IST collaborative project HURRICANE [185] [193] [192]. The entities designed and developed under the scope of this thesis are highlighted in *dark blue*, more specifically the MIH, the NMM and the TMM, as well as the cross-layer entity (WiMAX Cross Layer Manager – WXLM) to communicate with the WiMAX Base Station (BS).

According to the IEEE 802.21 standard, two main alternatives emerge as possible architectural choices for future implementations. These are (i) the PoA/PoS and (ii) the non-PoA/PoS approaches [194]. Their main difference concerns the location of PoS functionality, which in the first case is placed in a PoA, while a non-PoA component is chosen in the second case. Both approaches are illustrated in Figure 6-1 and depicted in Table 6-1.

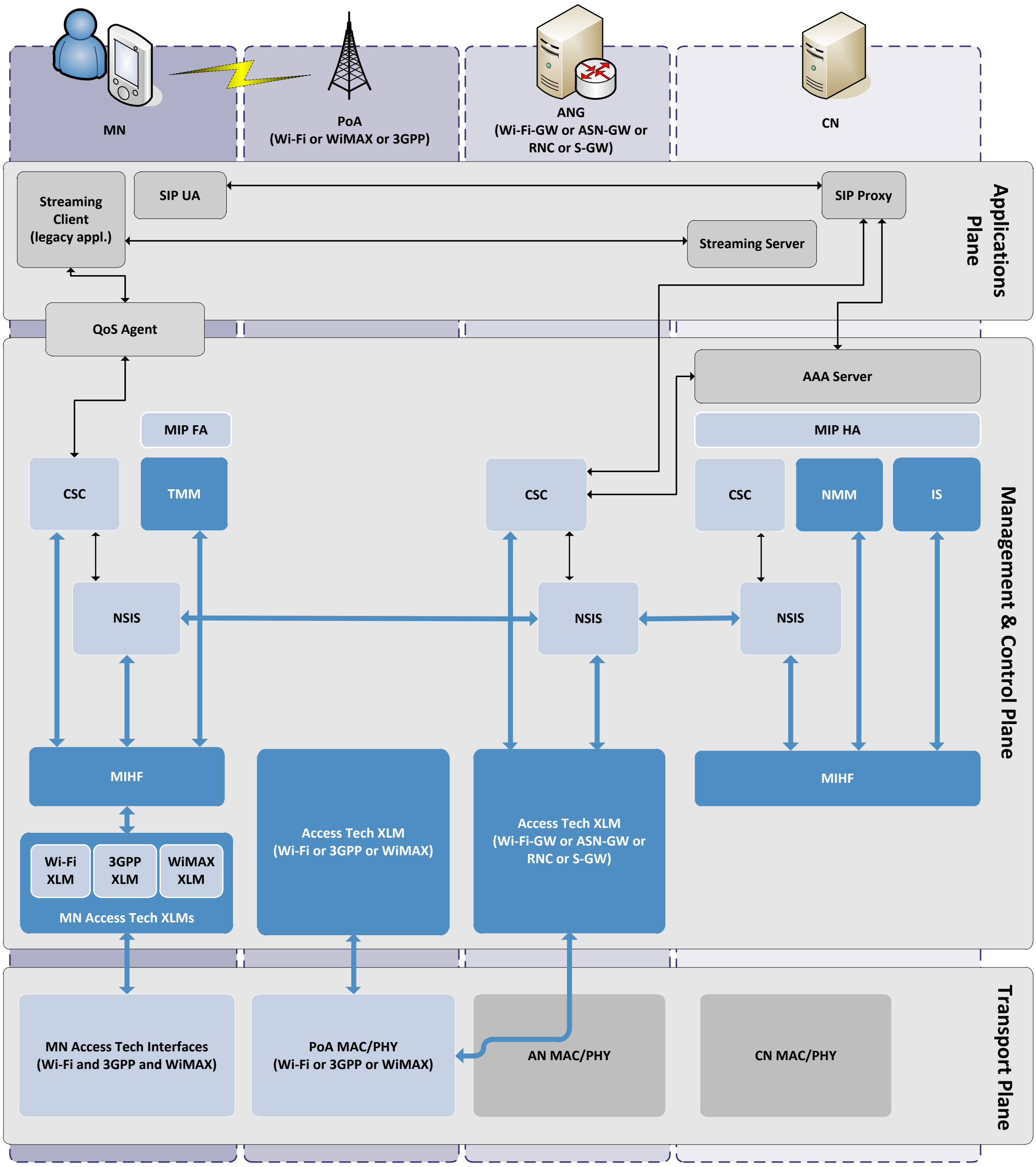

Figure 6-2: Inter-technology mobility architecture

With respect to the PoA/PoS approach, illustrated in Figure 6-1 with the blue dashed arrows, concerns the incorporation of IEEE 802.21 PoS functionality in the radio attachment node such as the Wi-Fi Access Point (AP), the WiMAX BS, the UMTS/HSPA NodeB (NB) or the LTE eNodeB (eNB). In this approach, the Wi-Fi AP, which is the Serving AN (SAN), according to the IEEE 802.21 communication model, is reachable from the MN through the 802.21 Reference Point 1 (RP1) interface. The remaining ANs, specifically WiMAX BS, UMTS NB and LTE eNB, are Candidate ANs (CANs) for the MIH MN and are reachable by the MIH MN through the 802.21 RP2 interface. The 802.21 RP5 interface is used to establish communication between the MIH PoSs, which, for this approach, correspond to the network PoAs.

Table 6-1: Mapping of IEEE 802.21 and AN entities

Access Network	Access Network Gateway (AN-GW)	Point of Attachment (PoA)	Point of Service (PoS)	
			PoA/PoS Approach	Non-PoA/PoS Approach
3GPP UMTS	Radio Network Controller (RNC)	NodeB (NB)	NB	RNC
3GPP LTE	Serving Gateway (S-GW)	eNodeB (eNB)	eNB	S-GW
WiMAX (IEEE 802.16e)	Access Service Network Gateway (ASN-GW)	Base Station (BS)	BS	ASN-GW
Wi-Fi (IEEE 802.11)	Wi-Fi GW	Access Point (AP)	AP	Wi-Fi GW

Alternatively, in the non-PoA/PoS approach, illustrated in Figure 6-1 with green solid arrows, any PoS functionality in the ANs is moved closer to the CN, with the WiMAX Access Service Network (ASN-GW), the Wi-Fi Gateway (GW), the UMTS Radio Network Controller (RNC) and the LTE Serving Gateway (S-GW) supporting the MIH operations. Since PoSs are implemented in network nodes that are not PoAs, the RP3 interfaces are used for inter-MIH protocol communication with the MIH MN, with the aid of a layer 3 MIH transport mechanism.

Table 6-2: Mapping of IEEE 802.21 interfaces with the AN entities

802.21 Interfaces	PoA/PoS Approach	Non-PoA/PoS Approach
RP1	MN ←→ AP	--
RP2	MN ←→ BS, eNB, NB	--
RP3	--	MN ←→ Wi-Fi GW, ASN-GW, RNC, S-GW
RP4	IS ←→ AP, BS, eNB, NB	IS ←→ Wi-Fi GW, ASN-GW, RNC, S-GW
RP5	AP ←→ BS ←→ NB ←→ eNB	Wi-Fi GW ←→ ASN-GW ←→ RNC ←→ S-GW

Besides the mobility management entities, more precisely the NMM, TMM and MIP, the CN also holds the IEEE 802.21 Information Server (IS), a non-PoS entity, which is responsible to maintain a database that provides information services to the MIH network nodes. More precisely, the information provided by the IEEE 802.21 IS is very important for the mobility decision entities, either running on the network (e.g. NMM) or on the terminal side (e.g. TMM), providing valuable information to optimize the handover decision algorithms. The IS is logically connected to the PoS entities in the ANs through RP4 interfaces. The CN GW acts as the "frontier" with the Internet services. Table 6-2 depicts the 802.21 communication model interfaces mapping with the AN entities.

In the following section it is proposed a set of extensions for managing radio resources on the link layer access technologies through explicit MIH commands.

6.2. Radio Resources Management Support in IEEE 802.21

The mobility heterogeneous architecture presented in section 6.1 intends to provide seamless handovers between the various wireless access networks presented, that is, provide the end user with moving capabilities without service disruption within WiMAX, Wi-Fi, UMTS/HSPA and LTE RATs. One of the key elements to enable seamless handovers within the given architecture is the integration of the IEEE 802.21 MIH services, which optimizes the handover initiation and preparation phases of the handover procedure. For example, during the handover preparation phase, the MIH services provide a set of mechanisms to query the available CANs about their available resources, optimizing the mobility decision algorithms.

Furthermore, besides the important optimizations achieved through the integration of the IEEE 802.21 framework, radio resources management in the link layer access technologies is another critical aspect that must be supported within a mobility architecture to provide a seamless handover experience. More precisely, seamless handovers require the active support of QoS enforcement in the access technologies during the handover preparation process, guaranteeing that resources are available in the TAN before mobility management operations are completed. In other words, mobility management and QoS management procedures are fundamental for a seamless handover procedure and must not be dissociated.

Nevertheless, the IEEE 802.21 protocol does not provide the necessary mechanisms to manage radio resources on the wireless access technologies. Herein is proposed a new method for performing radio resources management at lower layers during handover using the 802.21 framework [192] [193] [194].

Figure 6-3 illustrates the novel functionalities for the IEEE 802.21 framework.

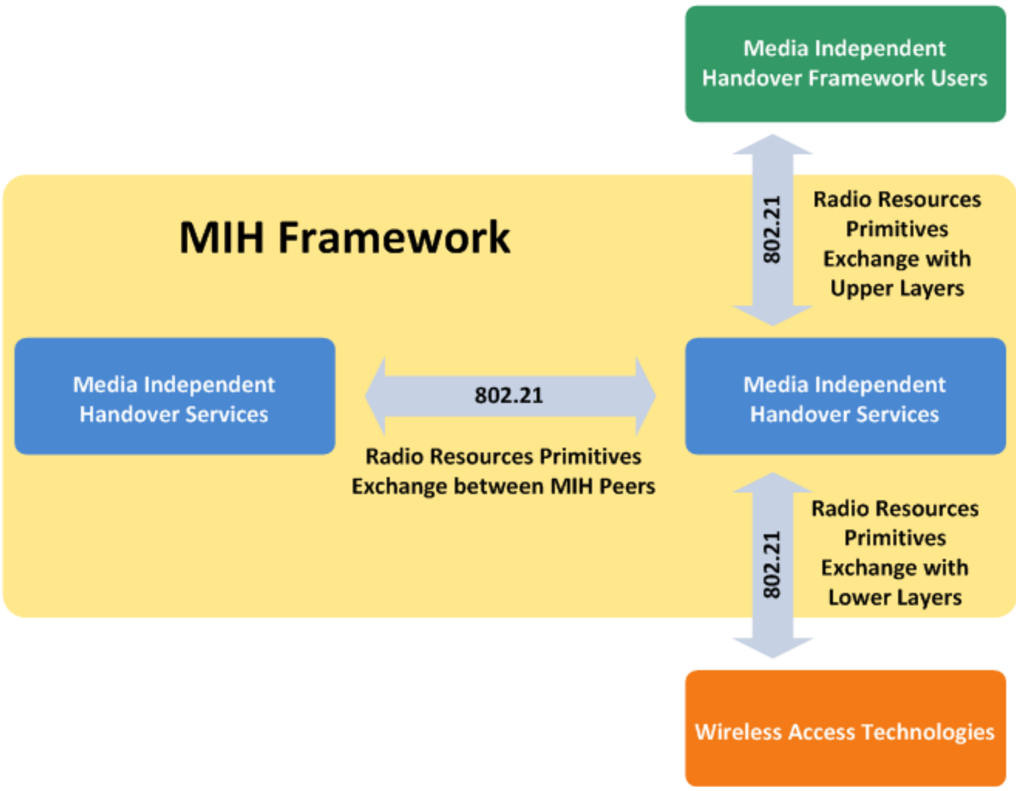

Figure 6-3: IEEE 802.21 service primitives for link layer resources management

6.2.1. MIH Radio Resources Management

The proposed functionalities extend the currently specified IEEE 802.21 Media Independent Command Service (MICS) by introducing explicit commands for radio resources reservation and deletion. The new functionalities are defined for the IEEE 802.21 MIH_SAP, MIH_LINK_SAP and MIH_NET_SAP interfaces and use the format of existing command messages in order to guarantee application in a future extension of the standard. The *MIH_Link_Actions* and *Link_Action* service primitives define a set of actions to control the access technologies, such as powering down and up the air interface. In order to manage radio resources on the access technologies, two additional actions for these service primitives are proposed, as depicted in Table 6-3, allowing the establishment of resources reservation and deletion in the wireless interface. More details about these primitives and the novel actions are described in the following subsections.

Table 6-3: Actions defined for *MIH_Link_Actions* and *Link_Action* service primitives

802.21 Primitive	Action Name	Description
MIH_Link_Actions* & *Link_Action* *(request / confirm)	***QOS_RESERVATION***	Triggers radio resources reservation procedure in the link layer access technologies: - 3GPP: triggers dedicated PDP (Packet Data Protocol) context activation; - WiMAX: triggers dedicated SF (Service Flow) activation; - Wi-Fi: triggers dedicated traffic flow activation.
	QOS_DELETION	Triggers radio resources deletion procedure in the link layer access technologies: - 3GPP: triggers dedicated PDP (Packet Data Protocol) context deactivation; - WiMAX: triggers dedicated SF (Service Flow) deactivation; - Wi-Fi: triggers dedicated traffic flow deactivation.

The proposed mechanism is applicable in cases where a MIH User (MIHU), which manages the network resources, triggers the resource reservation or deletion at lower layers. These actions may be performed either locally or remotely and are applicable to any RAT, including IEEE 802.16 (WiMAX), IEEE 802.11 (Wi-Fi) and UMTS/HSPA ANs. The following sections thoroughly describe the proposed resources management procedures, considering both mobile and network initiation reservations and deletions.

6.2.1.1. Local Resources Allocation

During the handover preparation phase the NMM selects the TAN for the handover and triggers the radio resources allocation process towards the Resource Manager (RM) at the TAN. The RM establishes the communication with the link layer for resources reservation using the proposed *MIH_Link_Actions.request (QOS_RESERVATION)* command, which contains all the required information about the QoS resources that must be allocated. In this case, the link layer on the network side initiates resources allocation procedure.

The MIHF at the TAN receives the *MIH_Link_Actions.request (QOS_RESERVATION)* and triggers the *Link_Action.request (QOS_RESERVATION)* command towards the local link layer. After the link layer resources allocation is completed, a report is sent upwards to the MIHF and thereafter to the RM using the *Link_Action.confirm (QOS_RESERVATION)* and *MIH_Link_Actions.confirm (QOS_RESERVATION)* primitives, respectively. This procedure is illustrated in Figure 6-4.

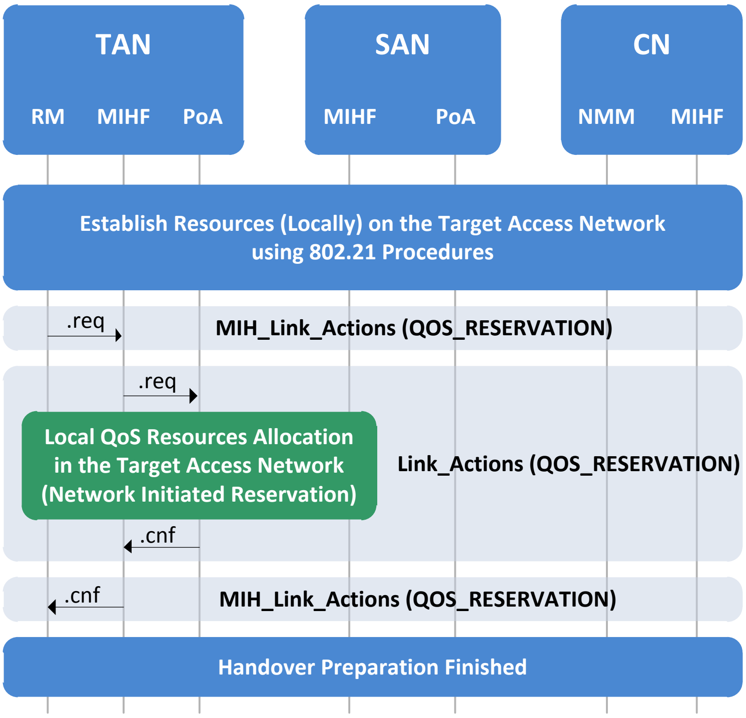

Figure 6-4: Local resources allocation MIH procedure

6.2.1.2. Remote Resources Allocation

For a remote resources allocation procedure, the RM at the TAN triggers the resources reservation in the wireless link using the proposed *MIH_Link_Actions.request (QOS_RESERVATION)* command, as illustrated in Figure 6-5.

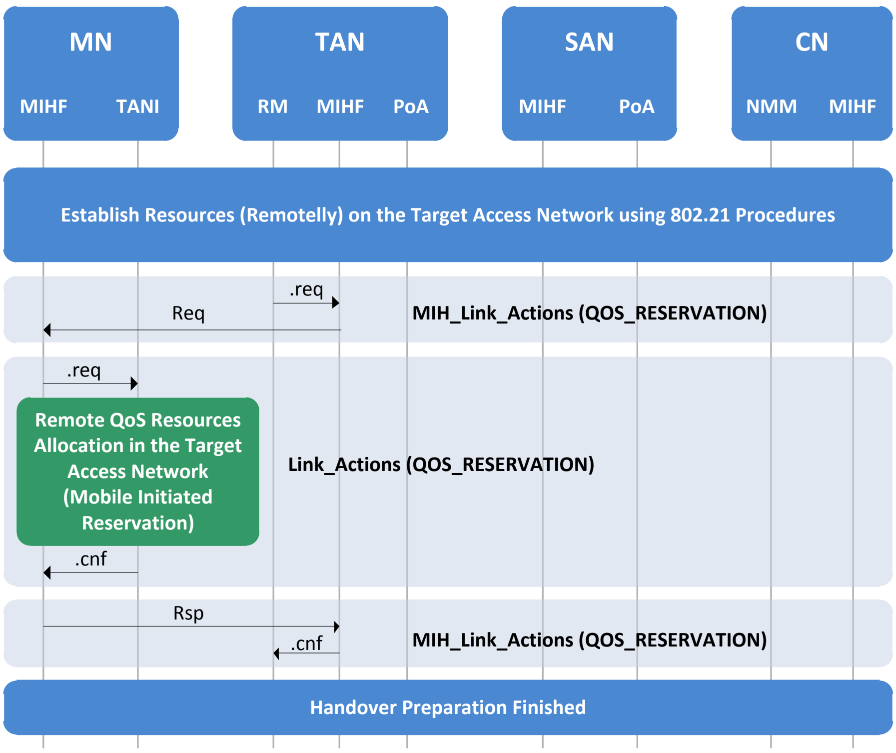

Figure 6-5: Remote resources allocation MIH procedure

Since in this case the resources must be allocated remotely via the MN wireless interface, the MIHF at the TAN triggers the *MIH_Link_Actions Request (QOS_RESERVATION)* message towards the MIHF at the MN through the MIH_NET_SAP interface, which will then be responsible for the local reservation on the wireless link using the *Link_Action.request (QOS_RESERVATION)* command via the MIH_LINK_SAP (through the Target Access Network interface).

A report with the allocation process result is sent back to the RM at the TAN using the *Link_Action.confirm (QOS_RESERVATION)*, *MIH_Link_Actions response (QOS_RESERVATION)* and the *MIH_Link_Actions.confirm (QOS_RESERVATION)* primitives. The complete remote resources allocation procedure is illustrated in Figure 6-5.

6.2.1.3. Local Resources Deletion

After the MN switches from the previous to the target wireless interface, data starts flowing through the new interface and the resources on the PAN must be released. To release the radio resources on the PAN, the NMM triggers the resources deletion procedure towards the RM at the PAN. The RM sends the proposed *MIH_Link_Action.request (QOS_DELETION)* command, as illustrated in Figure 6-6, to initiate the resources deletion procedure in the PAN.

The MIHF at the PAN receives the *MIH_Link_Actions.request (QOS_DELETION)* and triggers the *Link_Action.request (QOS_DELETION)* command towards the local link layer. After the link layer resources are released, a report is sent upwards to the MIHF and thereafter to the RM at the PAN using the *Link_Action.confirm (QOS_DELETION)* and *MIH_Link_Actions.confirm (QOS_DELETION)* primitives, respectively. This procedure is depicted in Figure 6-6.

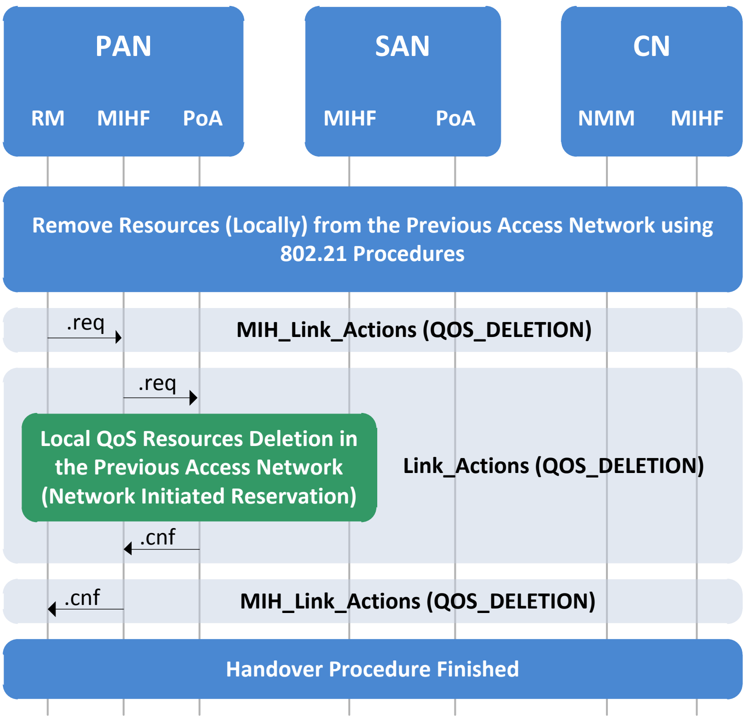

Figure 6-6: Local resources deletion MIH procedure

6.2.1.4. Remote Resources Deletion

For a remote resources deletion procedure, the RM at the PAN triggers the resources release in the wireless link using the proposed *MIH_Link_Actions.request (QOS_DELETION)* command, as illustrated in Figure 6-7. Since in this case the resources must be removed remotely via the MN wireless interface, the MIHF at the PAN triggers the *MIH_Link_Actions Request (QOS_DELETION)* message to the MIHF at the MN through the MIH_NET_SAP interface, which will then be responsible for the resources deletion on the wireless link using the *Link_Action.request (QOS_DELETION)* command through the MIH_LINK_SAP.

To announce the resources release result, a report is sent back to the RM using the *Link_Action.confirm (QOS_DELETION)*, *MIH_Link_Actions response (QOS_DELETION)* and the *MIH_Link_Actions.confirm (QOS_DELETION)* primitives. The complete remote resources allocation procedure is illustrated in Figure 6-7.

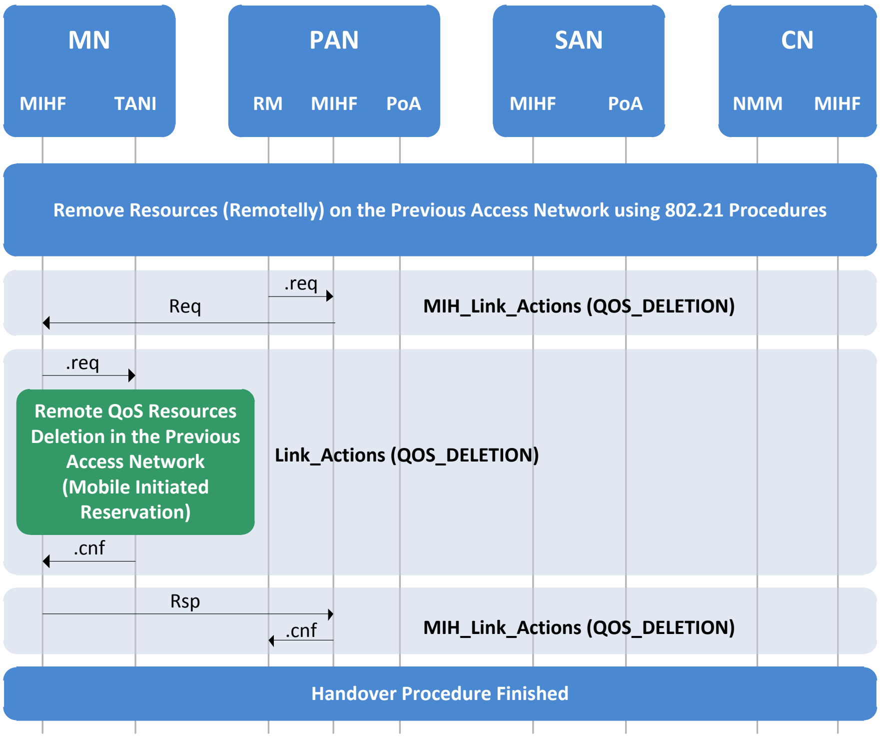

Figure 6-7: Remote resources deletion MIH procedure

6.3. MIH Based Seamless Handover Signaling with Radio Resources Management Integration

The previous sections discussed a seamless mobility architecture, including possible locations for the MIH entities within the Radio Access Network (RAN), as well as a set of extensions to the MIH framework to support radio resources management at the lower layers. In this section, a technology independent, IEEE 802.21 based description of a mobile-initiated, network-controlled handover procedure is described. This is an example of dual radio handover procedure wherein the network initiates the handover and both radios involved can transmit and receive simultaneously. The reference scenario and architecture are depicted in Figure 6-1 and Figure 6-2, where the respective interfaces between the MIH entities are presented according to the IEEE 802.21 standard. Message sequence charts are used to demonstrate the most important phases of the handover process: initiation, preparation, execution and completion.

6.3.1. Handover Initiation Phase

Initially, the MN is connected to the SAN and starts receiving traffic from an Application (APP) node on the Internet, as shown in Figure 6-1. The QoS parameters required to efficiently support the service results in configuration of the thresholds by the NMM, for which the link layer will report measurements to the MIH layers. This is done using the *MIH_Link_Configure_Thresholds.request* and *Link_Configure_Thresholds.request* service primitives in the Serving Access Network Interface (SANI).

After successful link threshold configuration, the NMM waits for periodical measurement reports from the SANI. These reports are transferred from the SANI in the MN to the MIHF and thereafter to the NMM through the *Link_Parameters_Report.indication and MIH_Link_Parameters_Report.indication* service primitives, respectively. In case any measurement report indicates a severe QoS degradation at the MN, an imminent handover is expected. This estimation report is transferred from the link layer through *Link_Going_Down.indication* service primitive to the MIHF and further to the NMM with a *MIH_Link_Going_Down.indication* service primitive. After collecting this information, the NMM at the SAN has information about the SANI link layer conditions in real-time and, if necessary, can trigger the handover preparation phase before the link goes down. Figure 6-8 illustrates the handover initiation phase procedures described above.

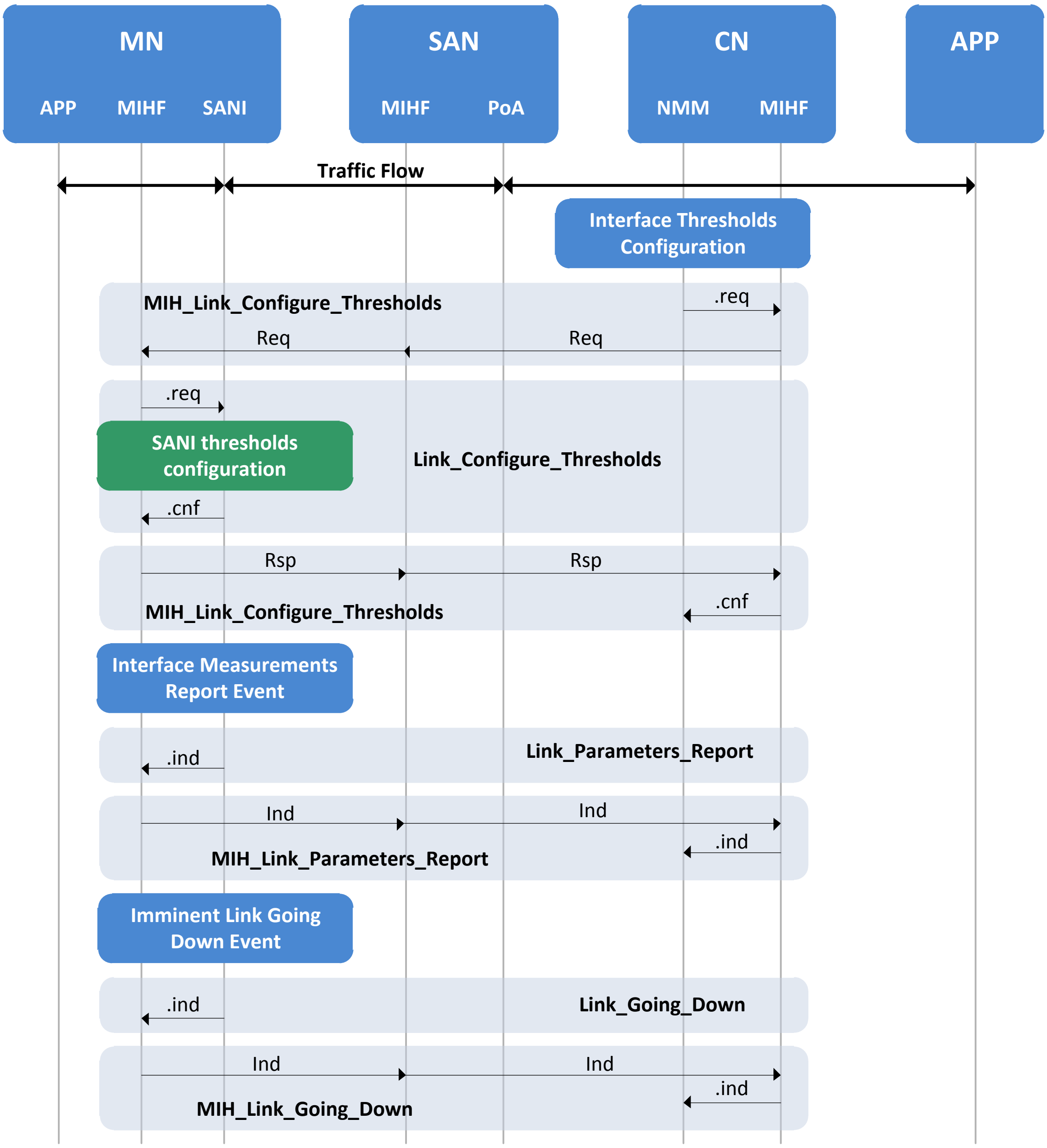

Figure 6-8: Handover initiation phase procedures

6.3.2. Handover Preparation Phase

6.3.2.1. Neighbor Access Networks Discovery

Immediately after receiving the *MIH_Link_Going_Down.indication* primitive, the NMM starts searching for a suitable neighbor AN. The NMM retrieves information about the neighboring networks by querying the IS through the *MIH_Get_Information* mechanism. This query reaches the respective database maintained in the IS. It can be based on the current PoA location, and its result returns the candidate networks (PoAs) near the MN, along with their characteristics. The last information is quite useful because it can help the MN later scan specific radio networks rather than every available network. It is important to note that the procedure of information retrieval from the IS can be in some scenarios the reason for initiating a handover (e.g., when opting for extra and better services or when optimizing radio resources usage).

If information for making the handover decision is not sufficient, the NMM orders all neighboring CAN interfaces indicated by the result of the IS query (CAN_1 and CAN_2) to power on and perform scanning with the *MIH_Link_Actions* and *Link_Action* mechanisms. This provides more up-to-date information about reachable neighboring networks. Figure 6-9 illustrates the flow chart with the CAN discovery and scanning procedures from the handover preparation phase.

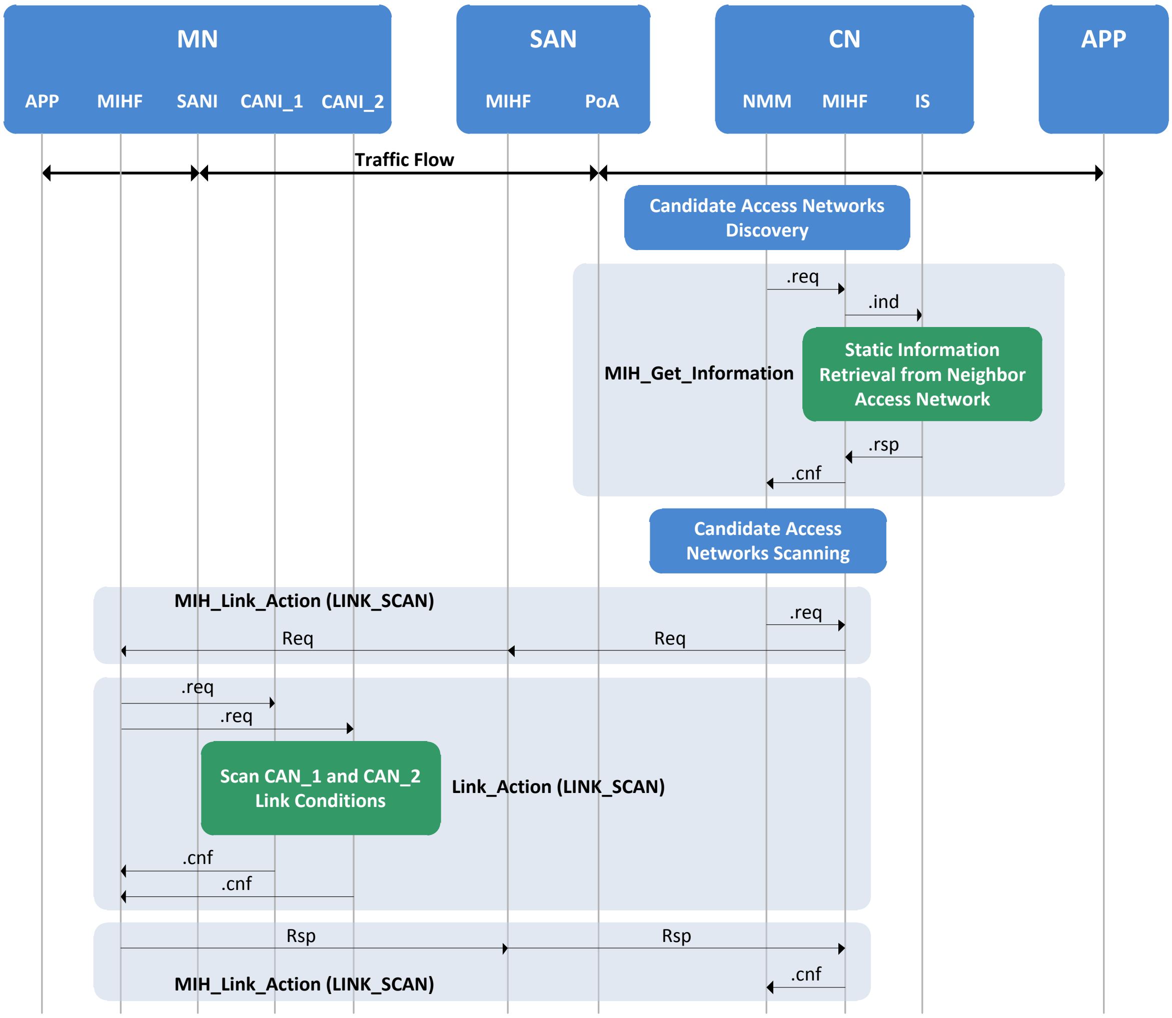

Figure 6-9: Handover preparation phase – CANs discovery and scanning procedures

6.3.2.2. Candidate Access Networks Resources Availability Check

Thereafter the NMM checks for the availability of the MN to handover and retrieves MN preferences regarding the CANs by exchanging *MIH_Net_HO_Candidate_Query* messages with the MN. After retrieving information from the surrounding access networks, the NMM identifies the resources availability status of the CANs by triggering the *MIH_N2N_HO_Query_Resources* mechanism towards the RM of each available CAN. Subsequently the RM at each CAN retrieves the resources availability information from their link layer by triggering the *MIH_Link_Get_Parameters* and *Link_Get_Parameters* mechanisms. After receiving the resources availability information from the link layer, each RM triggers provides this information to the NMM. This procedure must be repeated for each available CAN. The resources availability check procedure is illustrated in Figure 6-10.

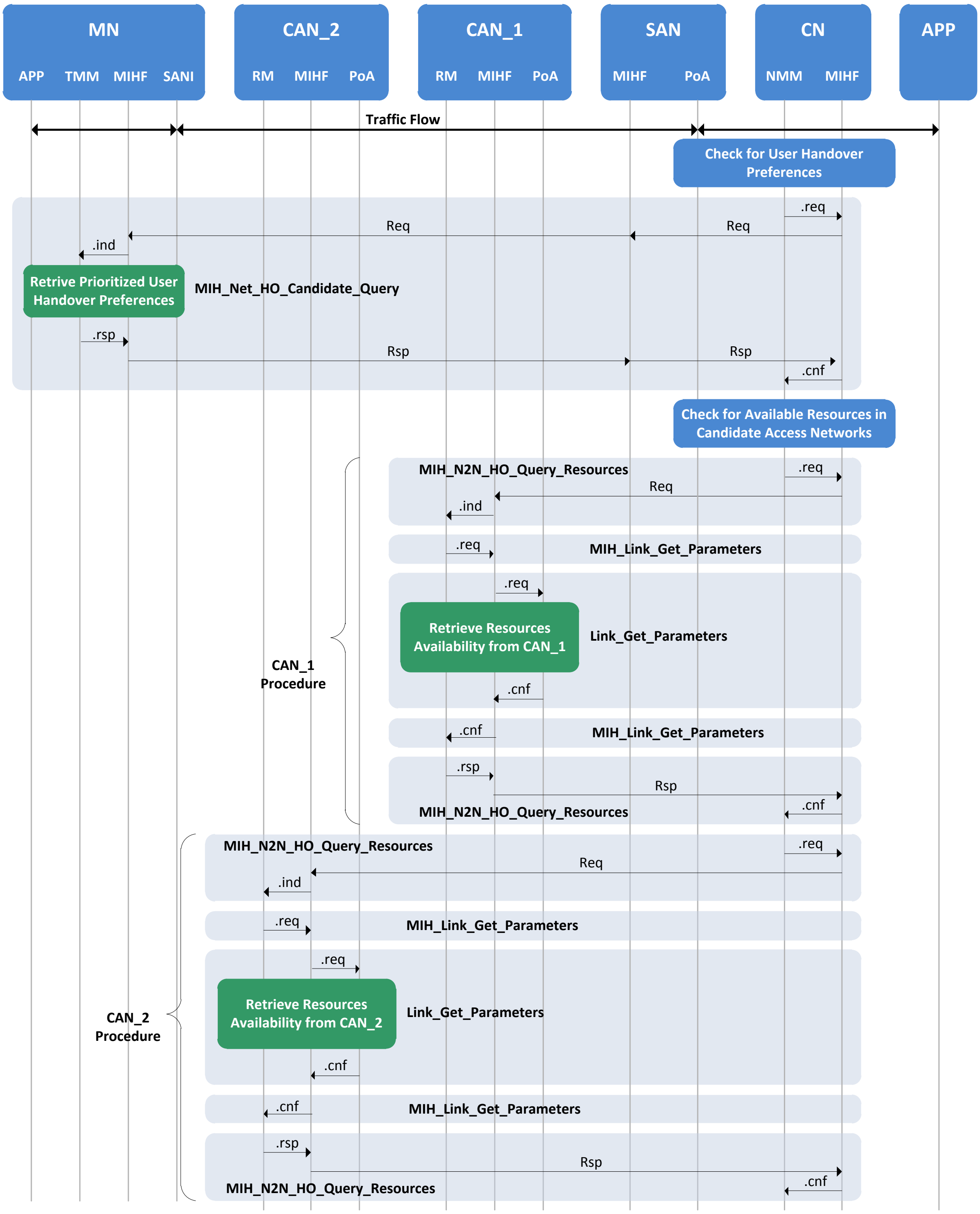

Figure 6-10: Handover preparation phase – CANs resources check procedure

6.3.2.3. Candidate Access Networks Interface Power Down/Up

Based on resource availability check, scanning results and other network information retrieved earlier from the IS, the CAN_1 is selected by the NMM as the TAN for handover. Right after this decision, any other interface previously powered on for scanning is now ordered to power off.

Thereafter, the NMM triggers the *MIH_Link_Actions* and *Link_Action* mechanisms to establish layer 2 connectivity with the selected AN. Figure 6-11 illustrates the interfaces power down/up.

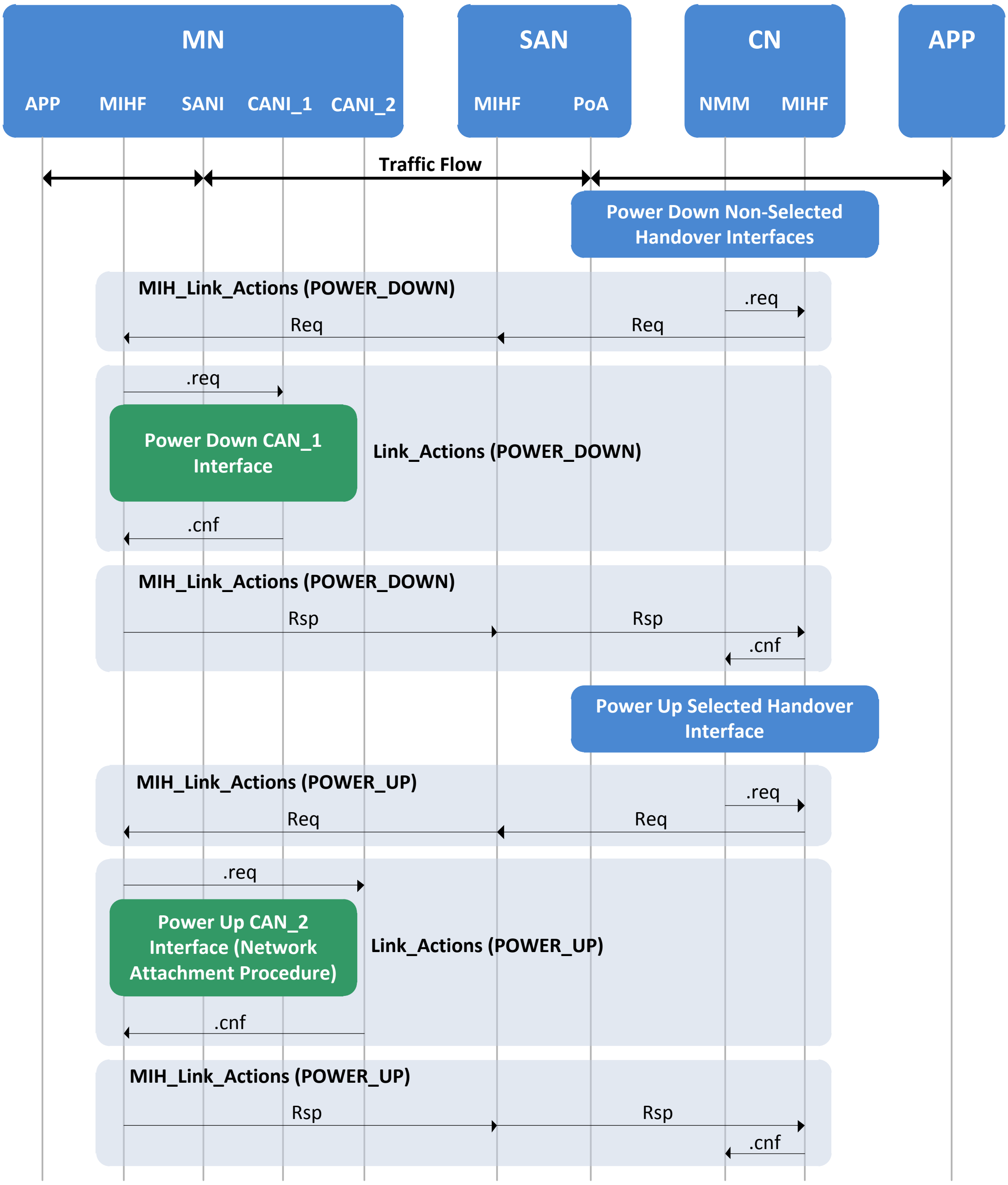

Figure 6-11: Handover preparation – power down/up access interfaces

6.3.2.4. Target Access Network Resources Reservation

Finally, before executing the handover from the old to the new AN, the NMM must reserve the required resources in the later. The *MIH_N2N_HO_Commit.request* message is sent to the RM in the TAN to notify it about the decided target network information. After receiving this message, the RM triggers the *MIH_Link_Actions.request/confirm (QOS_RESERVATION)* messages to communicate directly with the link layer access technology. It is important to mention that the resource reservation procedure could be performed in parallel with the connection establishment procedure.

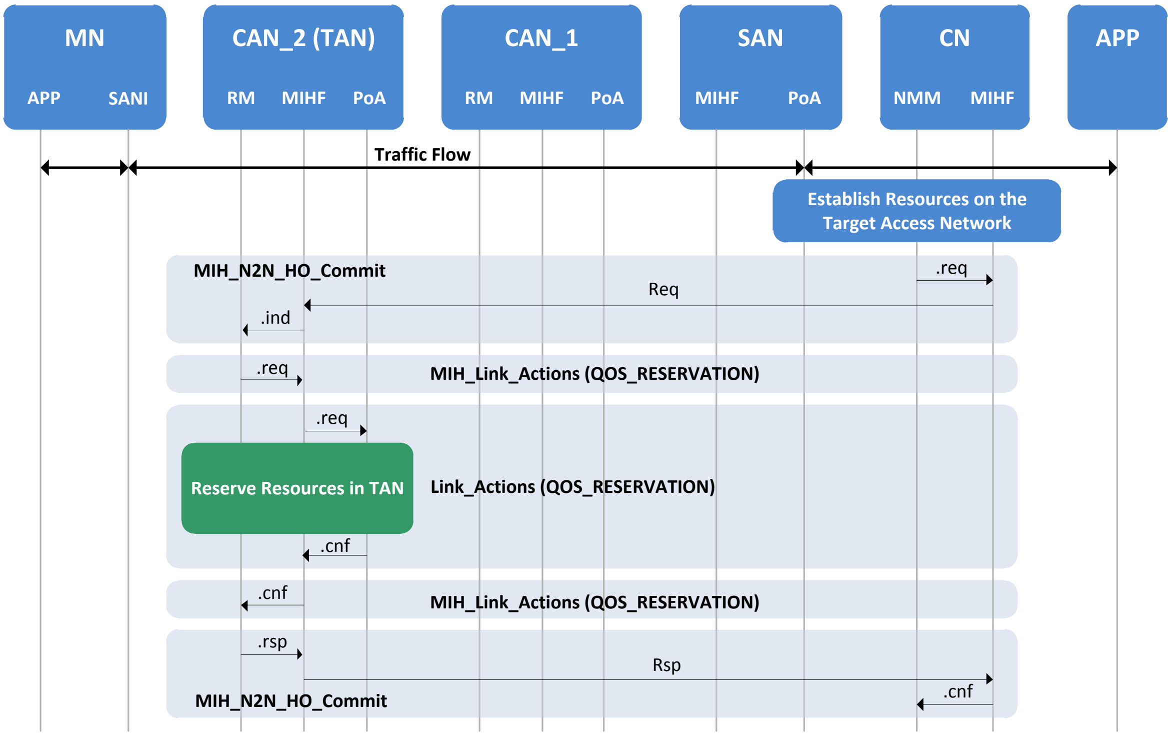

Figure 6-12: Handover preparation – target network resources reservation

6.3.3. Handover Execution Phase

After the handover preparation phase, the NMM triggers the IP mobility management procedures. As a result, the data flow is now shifted from the SAN to the TAN.

6.3.4. Handover Completion Phase

The NMM triggers the *MIH_N2N_HO_Complete* mechanism to the RM in the PAN to release the resources previously allocated for the MN, schedule to power off the previous interface and finalize the handover procedure. The RM sends the *MIH_Link_Actions.request/confirm (QOS_DELETION, POWER_DOWN)* messages. As in handover preparation (resource reservation), both local and remote ways of executing the link commands are possible. Finally, the successful completion of the handover is reported back to the NMM (*MIH_MN_HO_Complete.response (Status=success)*).

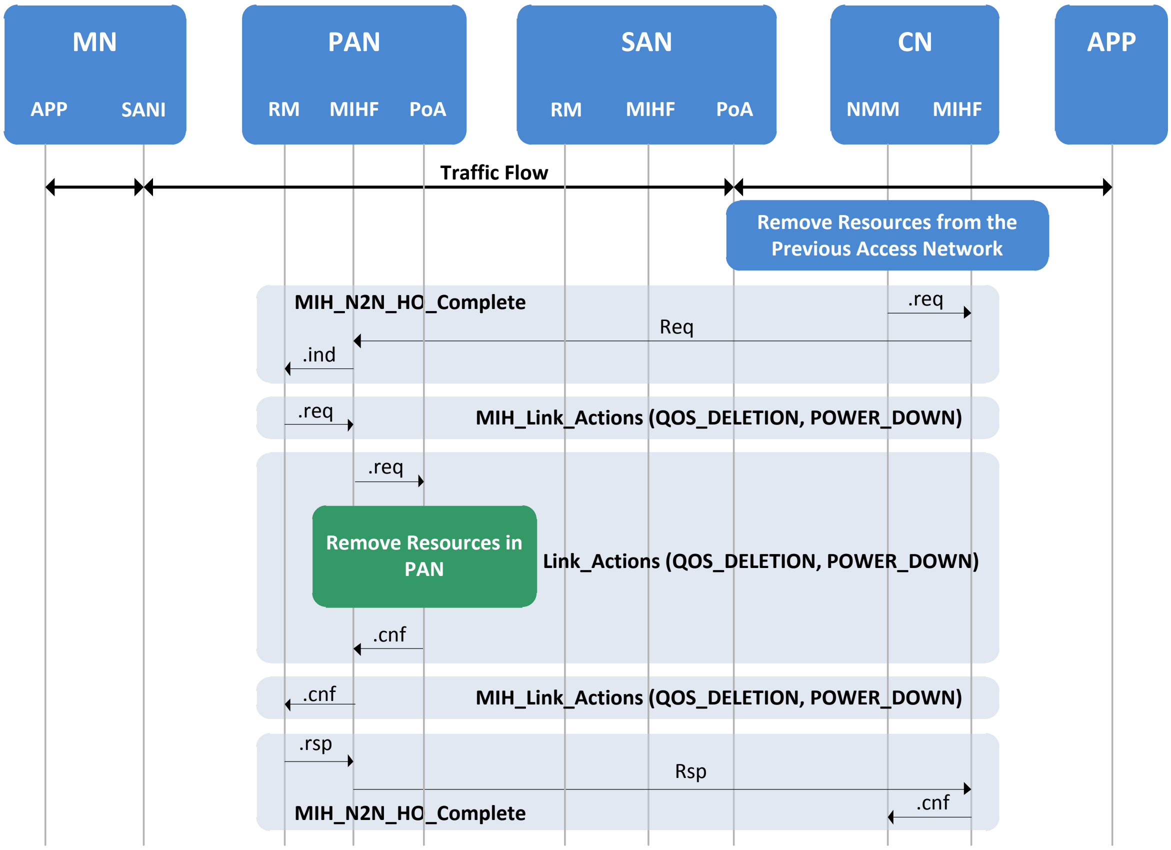

Figure 6-13: Handover completion phase

The following section provides further details about the integration of each one of the RATs (WiMAX, Wi-Fi and UMTS/HSPA) with the IEEE 802.21 primitives.

6.4. Media Specific Primitives Enhancements

In the previous section, a technology independent, IEEE 802.21-based seamless handover mechanism was proposed. A thorough description of the required signaling mechanisms for each one of the handover phases (initiation, preparation, execution and conclusion) was provided, and the required actions and interactions with the link layer access technologies were also identified. Nevertheless, no description was given about the integration of the IEEE 802.21 functionalities with the link layer access technologies.

The main objective of this section is to provide the missing description regarding the integration of the IEEE 802.21 functionalities with the RATs specific procedures and interfaces. More precisely, IEEE 802.21 provides a generic and technology independent interface with the upper layers, also known as MIH_SAP, as well as a set of media dependent lower-layer interfaces with the radio access technologies, which is a technology-specific instantiation of the MIH_LINK_SAP. Figure 6-14 illustrates the MIH_LINK_SAP to media specific primitives translator located on the MIHF. For the WiMAX access technology case, the translation is made on the Media Independent Management Service (MIMS) from the WXLM.

The integration of media-dependent interfaces within the MIHF facilitates the adoption of the IEEE 802.21 standard by the access technologies standardization bodies. The MIHF supports media-dependent interfaces with Wi-Fi, WiMAX and 3GPP based RATs. The MIHF uses the existing primitives and functionalities provided by different access technology standards for the most cases. Nevertheless, there is still a subset of IEEE 802.21 MIH_LINK_SAP primitives that is not mapped to any media-specific primitive. Furthermore, the proposed QoS resource management primitives in section 6.2 also lacks integration with the access technologies.

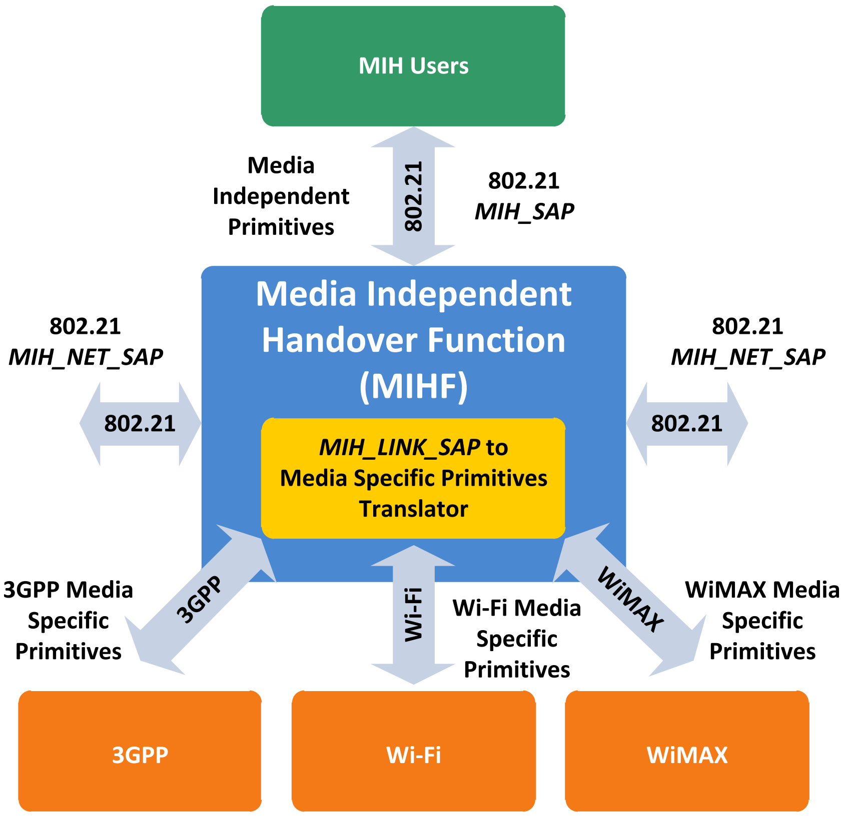

Figure 6-14: MIH_LINK_SAP and media specific primitives integration

The mapping of the IEEE 802.21 MIH_LINK_SAP primitives with the Wi-Fi, WiMAX and UMTS/HSPA link layer primitives will be depicted in the following subsections. Each one of the handover phases and internal steps will be described synchronized with the message sequence charts presented in section 6.3.

6.4.1. Wi-Fi

The interworking with external networks (and IEEE 802.21 in particular) is specified by the IEEE 802.11u standard [204].

Regarding interworking with IEEE 802.21, the IEEE 802.11u standard defines a new MAC State ConverGence Function (MSCGF) that provides additional services to the ones offered by the IEEE 802.11 standard. It is an extra level of "intelligence" for the wireless device and allows higher layers to efficiently extract link layer information as well as manage the wireless device appropriately.

The reference model of IEEE 802.11u is shown in Figure 6-15. As shown in this figure, the MSCGF has access to all management primitives and can provide information to higher layers through MAC_STATE_GENERIC_CONVERGENCE_SAP. MSGCF may access the MAC Sublayer Management Entity SAP (MLME_SAP) and the Physical Sublayer Management Entity SAP (PLME_SAP) directly or indirectly through the Station Management Entity (SME) using MSGCF-SME_SAP. Functions that are provided to higher layers by MSGCF are in accordance to the respective MIH primitives and include status reporting, network configuration, network events, and network commands.

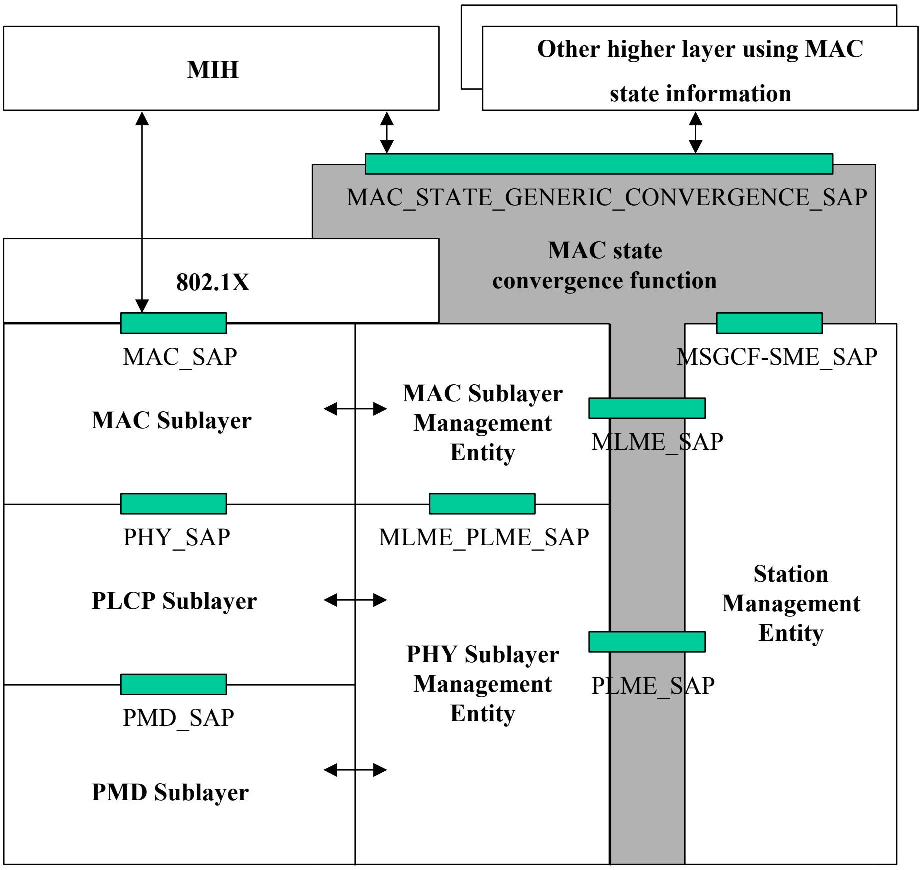

Figure 6-15: IEEE 802.11u reference model supporting IEEE 802.21 [192]

6.4.1.1. IEEE 802.21 and Wi-Fi Specific Primitives Integration

The integration of the IEEE 802.21 MIH_LINK_SAP primitives with the Wi-Fi media specific primitives is described in Table 6-4.

The primitives integration described in Table 6-4 are synchronized with the handover procedures identified in section 6.3. Moreover, the table also presents a summary of the control and management actions triggered by the primitives in the Wi-Fi link layer elements (SME, MLME and wireless link).

The proposed mapping, as depicted in Table 6-4, provides new QoS resources management functionalities for the *MSGCF-ESS-Link-Command* primitive – *MSGCF-ESS-Link-Command (QOS_RESERVATION)* and *MSGCF-ESS-Link-Command (QOS_DELETION)*. IEEE 802.11u does not describe explicitly any link layer command for managing QoS resources. Network commands only include disconnection, power-on/off, low power and scanning and therefore efficient management of 802.11 resources is needed through the definition of new IEEE 802.11u primitives. Furthermore, the current *MSGCF-ESS-Link-Command* primitives lack any characterization (primitive type) concerning request or confirmation. A "request" and "confirm" types were added to the *MSGCF-ESS-Link-Command* primitives.

Table 6-4: IEEE 802.21 and IEEE 802.11u primitives mapping

<table>
<tr><th colspan="4">Handover Initiation Phase (Section 6.3.1)</th></tr>
<tr><th rowspan="2">Function</th><th colspan="2">Primitives</th><th rowspan="2">IEEE 802.11 Control and Management Actions
(SME → MLME → Air Link)</th></tr>
<tr><th>IEEE 802.21
(MIH_LINK_SAP)</th><th>IEEE 802.11u
(MSGCF_SAP)</th></tr>
<tr><td>Configure Wi-Fi thresholds</td><td>Link_Configure _Thresholds</td><td>MSGCF-Set-ESS-Link-Parameters</td><td>Configure link layer thresholds</td></tr>
<tr><td>Obtain Wi-Fi link parameters</td><td>Link_Parameters _Report</td><td>MSGCF-ESS-Link-Threshold-report</td><td>Generate periodical and triggered measurement reports</td></tr>
<tr><td>Wi-Fi link going down</td><td>Link_Going_Down</td><td>MSGCF-ESS-Link-Going-Down</td><td>Report that the link is going down (based on predictive algorithms)</td></tr>
<tr><th colspan="4">Handover Preparation Phase (Section 6.3.2)</th></tr>
<tr><td>Scan Wi-Fi interface</td><td>Link_Action (LINK_SCAN)</td><td>MSGCF-ESS-Link-Command (SCAN)</td><td>Power-on wireless interface
[MLME-POWER-ON]
Scan the wireless link
[MLME-SCAN]</td></tr>
<tr><td>Query resources in candidate Wi-Fi</td><td>Link_Get_Parameters</td><td>MSGCF-Get-ESS-Link-Parameters</td><td>Retrieve network parameters</td></tr>
<tr><td rowspan="3">Establish Basic L2 Connectivity in Wi-Fi</td><td rowspan="3">Link_Action (POWER_UP)</td><td rowspan="3">MSGCF-ESS-Link-Command (POWER_UP)</td><td>Join (synchronize with BSS)
[MLME-JOIN]</td></tr>
<tr><td>Authentication
[MLME-AUTHENTICATE]</td></tr>
<tr><td>Association
[MLME-ASSOCIATE]</td></tr>
<tr><td>Commit resources in target Wi-Fi</td><td>Link_Action (QOS_RESERVATION)</td><td>MSGCF-ESS-Link-Command (QOS_RESERVATION)</td><td>Execute the connection establishment procedures
[MLME-ADDTS]</td></tr>
<tr><th colspan="4">Handover Completion Phase (Section 6.3.4)</th></tr>
<tr><td>Delete resources in previous Wi-Fi</td><td>Link_Action (QOS_DELETION)</td><td>MSGCF-ESS-Link-Command (QOS_DELETION)</td><td>Remove the established connections
[MLME-DELTS]</td></tr>
<tr><td>Power-off Wi-Fi interface</td><td>Link_Action (POWER_DOWN)</td><td>MSGCF-ESS-Link-Command (POWER_DOWN)</td><td>Power off the wireless interface</td></tr>
</table>

Table 6-5 briefly summarizes the new actions that were created for the *MSGCF-ESS-Link-Command* primitive.

Table 6-5: *MSGCF-ESS-Link-Command* primitive new actions

Wi-Fi Primitive	Action Name	Description	
MSGCF-ESS-Link-Command	*QOS_RESERVATION*	*.request*	Trigger QoS reservation in the Wi-Fi access link. As a result, the SME triggers the *MLME-ADDTS.request* using the QoS parameters from the *RequestedResources* field
		.confirm	The higher layers are informed about the result of the command. This reply is based on the results of the *MLME-ADDTS.confirm* message received by the SME. In case of ResultCode='SUCCESS', any assigned resources are described in the *AssignedResources* field
	QOS_DELETION	*.request*	Trigger QoS deletion in the Wi-Fi link. As a result, the SME triggers the *MLME-DELTS.request* message
		.confirm	The higher layers are informed about the result of the command. This reply is based on the results of the *MLME-DELTS.confirm* message received by the SME

6.4.2. WiMAX

IEEE 802.16 standard reference model is composed by the data, control, and management planes. The data plane protocol stack includes the PHY and the MAC layers. In order to integrate the IEEE 802.16 standard in an all-IP environment, the IEEE 802.16g standard [41] was published, an amendment to IEEE 802.16d. IEEE 802.16g defines the control and management plane functionalities, enabling interoperability with higher layers. The Network Control and Management System (NCMS), defined by IEEE 802.16g and illustrated in Figure 6-16, is an abstraction representing the higher layer control and management entities, enabling the PHY and MAC layers to be independent of the network architecture.

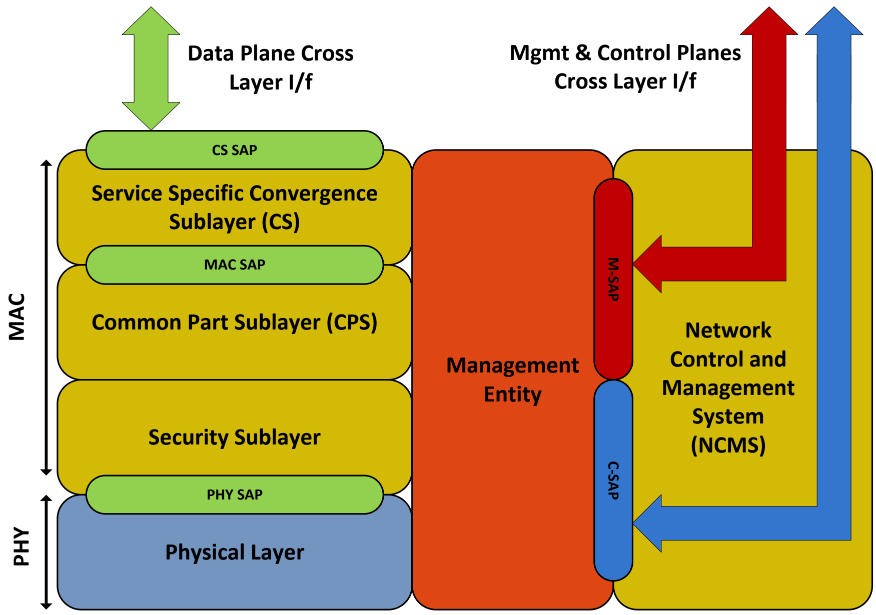

Figure 6-16: IEEE 802.16g reference model supporting IEEE 802.21 [192]

The IEEE 802.16g standard defines the Control SAP (C-SAP) and the Management SAP (M-SAP), responsible for exposing the control and management plane functions to the higher layers, respectively.

The M-SAP is used for less time-sensitive management plane functionalities related with system configuration, monitoring statistics, notifications, triggers and multimode interface management. The C-SAP is used for time-sensitive control plane functionalities such as handovers, mobility management, radio resource management, MIH services and SF management.

6.4.2.1. IEEE 802.21 and WiMAX Specific Primitives Integration

The integration of the IEEE 802.21 MIH_LINK_SAP primitives with the WiMAX media specific primitives is described in Table 6-6.

Table 6-6: IEEE 802.21 and IEEE 802.16g primitives mapping

Handover Initiation Phase (*Section 6.3.1*)			
Function	**Primitives**		**IEEE 802.16 Control and Management Actions (MAC → Air Link)**
	IEEE 802.21 (MIH_LINK_SAP)	**IEEE 802.16g (C_SAP & M_SAP)**	
Configure WiMAX thresholds	*Link_Configure _Thresholds*	*C-HO-REQ/RSP (HO-SCAN)*	Configure link layer thresholds
Obtain WiMAX link parameters	*Link_Parameters _Report*	*C-HO-IND (HO-SCAN)* or *C-HO-RSP (HO-SCAN)*	Generate measurement reports
WiMAX link going down	*Link_Going_Down*	***C-HO-IND (HO-LinkGoingDown)***	Report that the link is going down (based on predictive algorithms)
Handover Preparation Phase (*Section 6.3.2*)			
Scan WiMAX interface	*Link_Action (LINK_SCAN)*	*M-SSM-REQ/RSP (POWER_ON) C-HO-REQ/RSP (HO-SCAN)*	Power-on wireless interface Scan the wireless link *[DL_MAP, UL_MAP, DCD and UCD]*
Query resources in candidate WiMAX	*Link_Get_Parameters*	*C-RRM-REQ/RSP (Spare Capacity Report)*	Retrieve network parameters
Establish Basic L2 Connectivity in WiMAX	*Link_Action (POWER_UP)*	*C-NEM-REQ/RSP (Ranging)*	Ranging *[RNG-REQ/RSP]*
		C-NEM-REQ/RSP (SS Basic Capability)	SS Basic Capability Discover *[SBC-REQ/RSP]*
		C-NEM-REQ/RSP (Registration)	Registration *[REG-REQ/RSP]*
Commit resources in target WiMAX	*Link_Action (QOS_RESERVATION)*	***C-SFM-REQ/RSP (Create)***	Allocate a Service Flow for data transfer *[DSA-REQ/RSP/ACK]*
Handover Completion Phase (*Section 6.3.4*)			
Delete resources in previous WiMAX	*Link_Action (QOS_DELETION)*	***C-SFM-REQ/RSP (Delete)***	Remove the allocated Service Flow *[DSD-REQ/RSP/ACK]*
Power-off WiMAX interface	*Link_Action (POWER_DOWN)*	*M-SSM-REQ/RSP (POWER_DOWN)*	Power off the wireless interface

The primitives described in Table 6-6 are synchronized with the handover procedures identified in section 6.3. Moreover, the table also presents a summary of the control and management actions triggered by the primitives in the WiMAX link layer elements (MAC management entity and wireless link).

The mapping defined in Table 6-6 proposes the integration of the IEEE 802.16g *C-SFM-REQ/RSP* primitive to establish (*C-SFM-REQ/RSP (Create)*) and remove (*C-SFM-REQ/RSP (Delete)*) resources in the WiMAX system during the handover procedures. IEEE 802.16g does not describe explicitly any link layer command for providing information about the link going down. The indications provided by the *C-HO-IND* primitive only includes information about the handover initiation, cancelation and completion, as well as link scanning. Therefore a new action (*HO-LinkGoingDown*) is proposed to notify the upper layers that the WiMAX is going down within a predicted period of time.

Table 6-7 briefly depicts the new action that was created for the *C-HO-IND* primitive.

Table 6-7: *C-HO-IND* primitive new action

WiMAX Primitive	Action Name	Description
C-HO-IND	***HO-LinkGoingDown***	Indicates that the WiMAX wireless link is going down soon.

6.4.3. 3GPP UMTS/HSPA

MIH_3GLINK_SAP provides a set of primitives for mapping the IEEE 802.21 MIH_LINK_SAP primitives with the signaling functions of the UMTS/HSPA system, eliminating the need for new UMTS/HSPA primitives and protocols. In other words, MIHF translates the media-specific UMTS/HSPA link layer information needed by the higher layers in the mobility management protocol stack to perform the handovers between heterogeneous networks. Figure 6-17 illustrates the MIH_3GLINK_SAP interface.

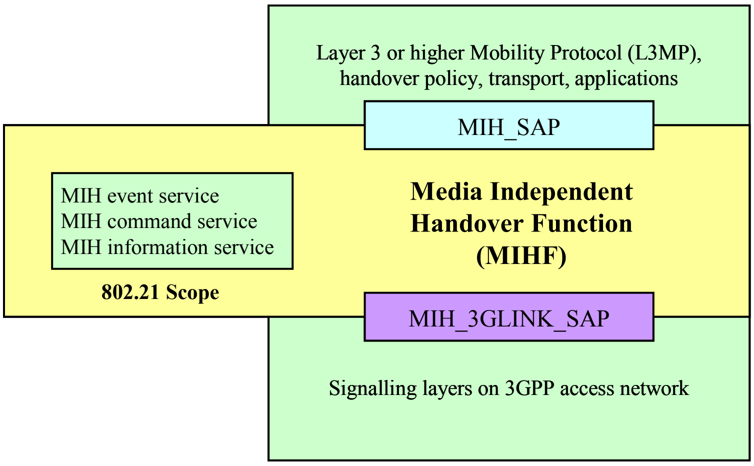

Figure 6-17: UMTS/HSPA Reference Model Supporting IEEE 802.21 [192]

6.4.3.1. IEEE 802.21 and UMTS/HSPA Specific Primitives Integration

The integration of the IEEE802.21 MIH_LINK_SAP primitives with the UMTS/HSPA media specific primitives is described in Table 6-8.

Table 6-8: IEEE 802.21 and UMTS/HSPA primitives mapping

<table>
<tr><th colspan="4">Handover Initiation Phase (Section 6.3.1)</th></tr>
<tr><th rowspan="2">Function</th><th colspan="2">Primitives</th><th rowspan="2">UMTS/HSPA Control and Management Actions
(MAC → Air Link)</th></tr>
<tr><th>IEEE 802.21
(MIH_LINK_SAP)</th><th>UMTS/HSPA
(SMREG-SAP;
RABMSM_SAP &
GMREG_SAP)</th></tr>
<tr><td>Configure UMTS/HSPA thresholds</td><td>Link_Configure _Thresholds</td><td>SMREG-PDP-MODIFY</td><td>Configure link layer thresholds</td></tr>
<tr><td>Obtain UMTS/HSPA link parameters</td><td>Link_Parameters _Report</td><td>RABMSM-MODIFY</td><td>Generate measurement reports</td></tr>
<tr><td>UMTS/HSPA link going down</td><td>Link_Going_Down</td><td>MEASUREMENT REPORT (Event Triggered)</td><td>Report that the link is going down (based on predictive algorithms)</td></tr>
<tr><th colspan="4">Handover Preparation Phase (Section 6.3.2)</th></tr>
<tr><td>Scan UMTS/HSPA interface</td><td>Link_Action (LINK_SCAN)</td><td>POWER_ON</td><td>Power-on wireless interface
Scan the wireless link
[Synchronization Channel]
[MN switches from DETACHED to IDLE mode]</td></tr>
<tr><td>Query resources in candidate UMTS/HSPA</td><td>Link_Get_Parameters</td><td>PAGING Type 1</td><td>Pages the MN to initiate RRC setup</td></tr>
<tr><td>Establish Basic L2 Connectivity in UMTS/HSPA</td><td>Link_Action (POWER_UP)</td><td>GMMREG-ATTACH</td><td>Attach to the UMTS/HSPA network
[GMM Attach]</td></tr>
<tr><td>Commit resources in target UMTS/HSPA</td><td>Link_Action (QOS_RESERVATION)</td><td>SMREG-PDP-ACTIVATE</td><td>Allocate a PDP Context for data transfer
[SM Activate PDP Context
RRC Radio Bearer Setup]</td></tr>
<tr><th colspan="4">Handover Completion Phase (Section 6.3.4)</th></tr>
<tr><td rowspan="2">Delete resources in previous UMTS/HSPA</td><td rowspan="2">Link_Action (QOS_DELETION)</td><td>SMREG-PDP-DEACTIVATE</td><td>Deactivate PDP context
[SM Deactivate PDP Context]</td></tr>
<tr><td>GMMREG-DETACH</td><td>Detach from UMTS/HSPA network
[GMM Detach
RRC Radio Bearer Release]</td></tr>
<tr><td>Power-off UMTS/HSPA interface</td><td>Link_Action (POWER_DOWN)</td><td>POWER-OFF</td><td>Power off the UMTS/HSPA interface</td></tr>
</table>

Table 6-8 depicts the UMTS/HSPA and IEEE 802.21 primitives mapping, synchronized with the handover procedures identified in section 6.3. Moreover, the table also presents a summary of the control and management actions triggered by the primitives in the UMTS/HSPA link layer elements (MAC management entity and wireless link).

The proposed mapping proposes the integration of the *SMREG-PDP-ACTIVATE* primitive to establish resources in the UMTS/HSPA link. Regarding the resources release in the UMTS/HSPA link, the *SMREG-PDP-DEACTIVATE* primitive is selected to deactivate the PDP context, followed by the *GMMREG-DETACH* primitive to detach from the UMTS/HSPA network and to release the RRC radio bearer.

Furthermore, UMTS/HSPA does not provide a primitive to explicitly power on and power off the UMTS/HSPA interface. Therefore new messages were proposed to address these functionalities, allowing IEEE 802.21 to fully control the UMTS/HSPA interfaces during the seamless handover procedure. Table 6-9 briefly depicts the new *POWER-ON* and *POWER-OFF* primitives.

Table 6-9: UMTS/HSPA *POWER-ON* and *POWER-OFF* new primitives

UMTS/HSPA Primitive	Description	
POWER-ON	*.request*	This primitive is generated by the MIHF to power-on an inactive UMTS/HSPA interface. After receiving the *POWER-ON-REQ* primitive from the MIHF, the inactive UMTS/HSPA interface is powered on and enters cell search procedure thus enabling it to enter IDLE mode.
	.confirm	This primitive is used to confirm the execution of the power on procedure of the UMTS/HSPA interface. This primitive is generated as a result of the *POWER-ON-REQ* message to confirm that the MN has entered IDLE mode.
POWER-OFF	*.request*	This primitive is generated by the MIHF when there is a request to deactivate the UMTS/HSPA interface. After receiving the *POWER-OFF-REQ* primitive from the MIHF, the active UMTS/HSPA interface is powered down.
	.confirm	This is primitive is used to confirm the execution of the power off procedure of the UMTS interface. This primitive is generated as a result of the *POWER-OFF-REQ* message to confirm that the MN has entered DETACHED mode.

Within this chapter it has already been presented the scenario, architecture and signaling for inter-technology seamless handover procedures. In the remaining sections of this chapter it will be presented and discussed a set of inter-technology handover results obtained in two different environments: network simulator to address scalability tests (section 6.5) and real network commercial testbed to understand the behavior of the proposed architecture in already existing networks (section 6.6).

6.5. Simulation Performance Evaluation

In order to evaluate the proposed architecture in a large-scale environment, it was created a heterogeneous network access scenario in the Network Simulator (NS-2) tool [205] [206] to validate the seamless inter-technology handovers signaling diagrams depicted in Section 6.3.

Notice that the NS-2 simulator, by default, does not provide *make-before-break* handover mechanisms, but rather *break-before-make* techniques. Therefore, any handover performed would result in associated packet loss during the handover execution phase.

Section 6.5.1 describes the required modifications on the NS-2 simulator to support vertical handovers in heterogeneous access networks, section 6.5.2 provides the results for the several vertical handover phases signaling and section 6.5.3 provides a discussion about the handover impact on the running applications, using a set of QoS metrics for validation [188] [189].

6.5.1. NS-2 Modifications and Add-ons

Modifications to an already available NS-2 implementation of the IEEE 802.21 protocol developed by the NIST group [205] were made in order to improve the protocol implementation as well as to allow its full integration with the different wireless access technologies, in particular with UMTS.

6.5.1.1. IEEE 802.21 Framework Modifications and Add-ons

One of the major drawbacks of the IEEE 802.21 NIST add-on was the lack of support for the IEEE 802.21 entities on the network side, specifically the MIHU. Therefore there was only local communication with the MIHUs, missing the communication between MIHUs on the network and on the MN. To overcome this limitation and enable the communication between all the network entities, either local or remote, an MIHU was specified and implemented on the network side.

The new messages added to the IEEE 802.21 NS2 NIST software were the following:

- MIH commands:
    - *MIH_MN_HO_Candidate_Query;*
    - *MIH_N2N_HO_Query_Resources;*
    - *MIH_MN_HO_Commit;*
    - *MIH_Net_HO_Commit;*
    - *MIH_N2N_HO_Commit;*
    - *MIH_MN_HO_Complete;*
    - *MIH_N2N_HO_Complete.*
- MIH information:
    - *MIH_Get_Information.*

Furthermore, the available implementation only performs IEEE 802.21-based handovers when a *Link_Going_Down* event is detected. In this new upgrade, it is possible to perform a handover not only in a *Link_Going_Down* event case, but also when a *Link_Detected* event is received by the MIHU. This modification enables the mobility agent to trigger the handover to a neighbour access network with better performance, or pricing, is found.

6.5.1.2. UMTS Access Technology Modifications

The NS-2 NIST add-on only allowed for handovers between Wi-Fi and WiMAX. The handover concept between UMTS and other access technologies is not well defined in the simulator.

Theoretically the UMTS network MIH is supposed to be located on the NB. However, due to the simulator limitations it was not possible to install it on the NB and therefore the adopted solution was to install it on the RNC node and connect it to the NB MAC layer. Although the network MIH location for UMTS had no impact in a theoretical level, it had from the implementation point of view. More specifically, the *MIH_Link_Up* event, which was only available locally on the access technologies, had to be extended to support the UMTS network MIH.

Further modifications were required to allow the interaction between the IEEE 802.21 framework and the UMTS technology. The concept of mobility using an UMTS interface is inaccurate. In fact, what happens is that the MN is a stationary point that has no capability to move and is always in the NB range. However what is done is that, the UMTS UE (interface) is defined and associated to a MN, so wherever the MN is, it is connected to the UMTS interface. The disadvantage is that the MN never leaves the UMTS BS range, and there is no possibility to simulate handovers between UMTS cells.

Another issue about the UMTS implementation in the simulator is related with the MAC layer. When defining any type of device in NS-2, whether it is a router, a Wi-Fi/WiMAX BS or a MN interface, the simulator creates the MAC layer, and with it, a unique MAC address associated to the device. However this does not happen with the UMTS devices, namely the NB and the MN. According to the channels that are configured, DCH or HS-DCH, the MAC addresses change. The devices are created with a specific MAC address by the base MAC class, but are changed according to the configurations made in the UMTS specific MAC class. Major changes were made in the UMTS elements code to overcome this limitation.

The modified version of NS-2 NIST add-on can be found in [207].

6.5.2. Large-Scale Vertical Handover Signaling Measurements

6.5.2.1. Simulated Scenario and Tests Methodology

The wireless access technologies involved in our scenario are UMTS/HSPA, WiMAX and Wi-Fi, as illustrated in Figure 6-18.

IEEE 802.21 entities were integrated in the multimode MN, as well as on the AN and on the CN. The IEEE 802.21 IS was installed on the CN side, whereas the MIH PoS was installed on each one of the AN-GWs. Both mobile and network initiated handovers were considered, depending on whether the handover process is triggered on the terminal or on the network side, respectively. Three inter-technology handover scenarios are considered: 1) Wi-Fi to WiMAX, 2) WiMAX to UMTS and 3) UMTS to Wi-Fi, providing a case study for all the possible combinations between these radio access technologies.

The handover preparation phase, as one of the most critical phases of the mobility process, is thoroughly evaluated, depicting each one of its internal steps: 1) Neighbors ANs discovery (described in section 6.3.2.1), 2) CAN resources availability check (described in section 6.3.2.2) and 3) TAN resources reservation (described in section 6.3.2.4). Additionally, in order to provide a complete evaluation of the mobility procedure, this section also discusses the handover execution phase, presenting the handover delay, which is the time interval between the last packet received on the PAN interface and the first packet received on the TAN interface. Moreover, QoS measurements tests are also presented, specifically for the packets delay, loss and jitter during the handover procedure.

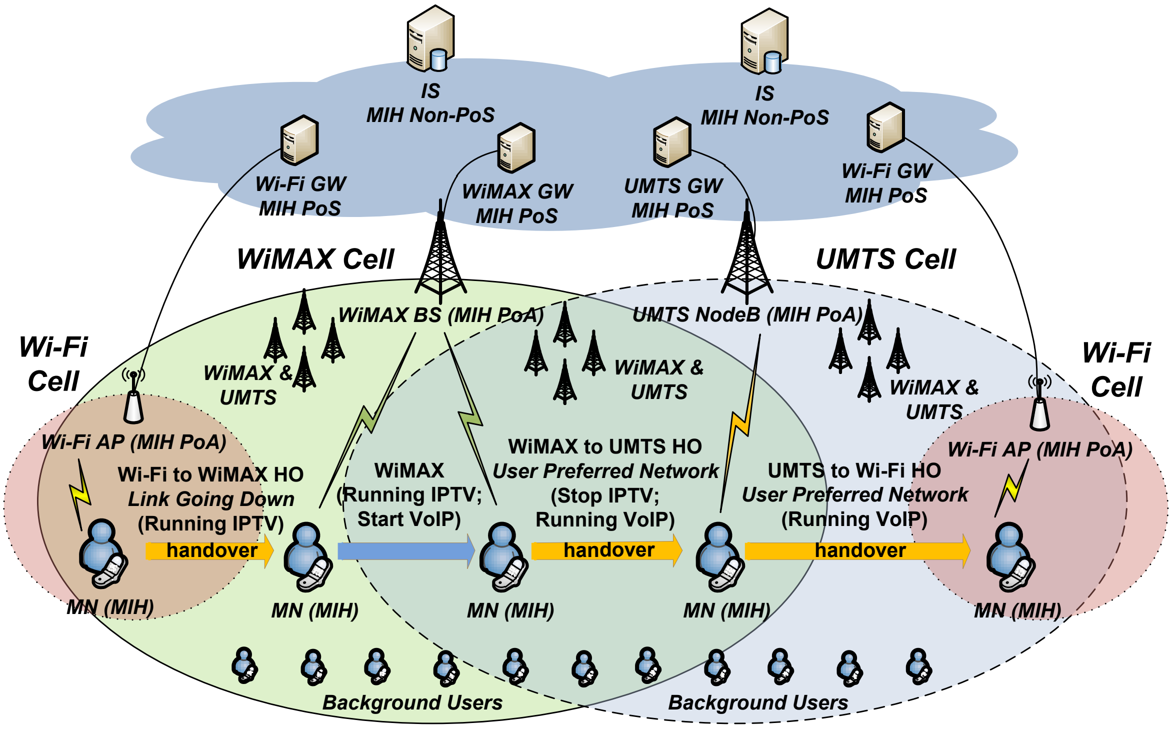

Figure 6-18: Inter-technology mobility simulation scenario

The simulation scenario integrates several background users, distributed across all the radio access technologies, each one generating Constant Bit Rate (CBR) data flows, exponentially distributed between 64 Kbps and 2 Mbps, with an average of 256 Kbps. Likewise, the MN is also generating an ongoing CBR data flow between 64 Kbps and 2 Mbps. The CBR data flows rates depend on the type of scenario, access technology and service. Although the three handover cases were tested for a large set of data rates, we selected the most relevant one for each handover to describe herein. More details about the chosen data rates for each handover scenario will be depicted in the following subsections. A brief overview about the access technologies data rates is provided in Table 6-10.

The information from the previous table is important to discuss the results obtained for each one of the handover scenarios. The presented simulation values represent the average of ten independent runs in the NS-2 simulator.

Table 6-10: RATs characteristics

Radio Access Technology	Data Rate	
	Total	Uplink / Downlink
WiMAX	40 Mbps	50 % Shared Channel (20 Mbps per direction)
Wi-Fi	11 Mbps	50 % Shared Channel (5.5 Mbps per direction)
UMTS/HSPA	384 Kbps	Dedicated Channel

6.5.2.2. Results

6.5.2.2.1 Wi-Fi to WiMAX Handover

Initially, the MN is connected to the Wi-Fi access technology and is receiving a 2 Mbps IPTV stream. The user is leaving his apartment (Wireless Local Area Network – WLAN) to the city center (Wireless Metropolitan Area Network – WMAN), and therefore a notification, more precisely a link going down, is sent by the IEEE 802.21 framework informing that the user is getting near to the Wi-Fi cell edge. Hence, in order to obtain a seamless make-before-break handover while receiving the IPTV stream, the terminal initiates a MIHO towards the available metropolitan radio access technology – WiMAX. The results obtained for the handover preparation phase, including the internal steps discussed in section 6.3.2, are illustrated in Figure 6-19. Each background user is injecting flows with 512 Kbps data rates.

As illustrated in the previous figure, the handover preparation phase takes approximately 125 milliseconds (ms) until the number of simultaneous background users is increased up to 6, which is the threshold limit for the Wi-Fi link saturation. The handover preparation time is distributed in three internal steps of the handover preparation phase: 35 ms for neighbor ANs discovery (*green*), 40 ms for CAN resources availability check (*purple*) and 50 ms for TAN resources reservation (*blue*). These values are easily explained due to the one-way delay of the Wi-Fi and the wired links. The one-way delay of the wired part of the network is approximately 5 – 10 ms for the three handover cases presented, whereas the one-way delay on the wireless link depends on the radio access technology. For the Wi-Fi link, the one-way delay is approximately 10 – 12 ms. The time interval spent on each internal step of this phase can be explained if we sum up all the one-way delays in the wireless and wired links. For example, the 35 ms spent by neighbor ANs discovery process are due to the *MIH_Get_Information.req* message sent from the MN to the IS (uplink Wi-Fi wireless hop and wired hop) and the *MIH_Get_Information.rsp* message sent from the IS to the MN (downlink wired hop and Wi-Fi hop). Summing the one-way delays associated with the wired and the wireless links (uplink and downlink) we obtain approximately 35 ms. The values measured for the CAN resources availability check and TAN resources reservations procedures have a similar justification.

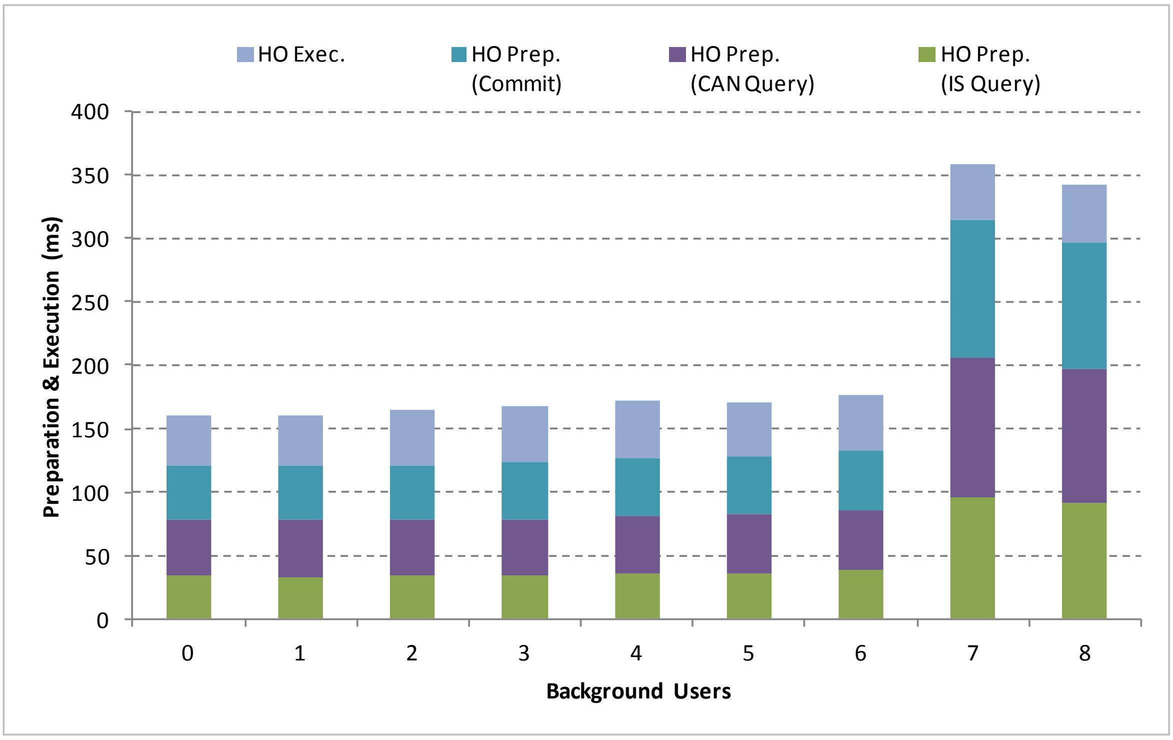

Figure 6-19: Wi-Fi to WiMAX handover preparation and execution phases

When the number of background users goes beyond 6, the wireless link saturates and the measured values start increasing significantly. For example, for 7 simultaneous background users, the total background traffic is approximately 3.6 Mbps (each background user injects 512 Kbps). Since the IPTV stream is 2 Mbps, the total data rate in the wireless channel is 5.6 Mbps, already surpassing the limit for the downlink channel of the Wi-Fi access technology (5.5 Mbps – Table 6-10).

The handover execution phase, illustrated in Figure 6-19, shows that the handover execution time (*light blue*) is approximately constant (45 ms) when the number of background users increases.

6.5.2.2.2 WiMAX to UMTS Handover

While in movement, the user receives an incoming VoIP call (128 Kbps rate). Consequently, it stops the IPTV video streaming. In order to satisfy the economic and technical user requirements, a list of preferred radio access technologies for the MN is agreed with the operator. The most preferred option is to be connected to Wi-Fi, secondly to UMTS and the last one via WiMAX. Although the user has a list of network preferences, the most important requirement is to have ubiquitous and seamless connectivity. This means that, when a preferred TAN is available and satisfies the requirements of the services running on the MN, the operator must initiate a NIHO procedure to the TAN. Since the user is running a VoIP call, and a UMTS cell is available in the MN geographical area, a NIHO is triggered from WiMAX to UMTS. The measured values for the WiMAX to UMTS preparation and execution handover phases are demonstrated in Figure 6-20.

Analyzing Figure 6-20, we can conclude that the total handover preparation time (36 ms) is approximately constant, independently of the number of background users. Since this is a typical NIHO scenario, the handover preparation phase internal steps are simpler because the MN does not have to intervene in the preparation procedures. Therefore, there is no communication with the MN, and consequently, the internal steps of the handover preparation phase are less time-consuming (neighbor ANs discovery – 12 ms; CAN resources availability check – 13 ms and TAN resources reservation – 11 ms) when compared with the ones from the Wi-Fi to WiMAX handover, in which the handover preparation time is around 125 ms. Since the wireless link does not intervene in the handover preparation phase, these values can be explained by the one-way delay given by the wired part of the network (one-way delay is approximately 5 – 10 ms). The increase in the background users does not affect the handover preparation phase because this is a NIHO scenario, and therefore, the wireless link is not involved in this phase.

For the handover execution phase, illustrated in Figure 6-20, the time interval is approximately 110 ms and constant. This time is spent on the link level association with the UMTS network and on the acquisition of a new IP address. Therefore, the performance of the handover execution phase heavily depends on the type of TAN to which the user is handing off. Since the UMTS network consumes a significant amount of time on the link layer association, the handover execution time for this scenario (110 ms) is more than duplicated compared with the handover execution time from the Wi-Fi to WiMAX handover (45 ms). Nevertheless, it is still able to seamlessly handover the MN services to the UMTS RAN.

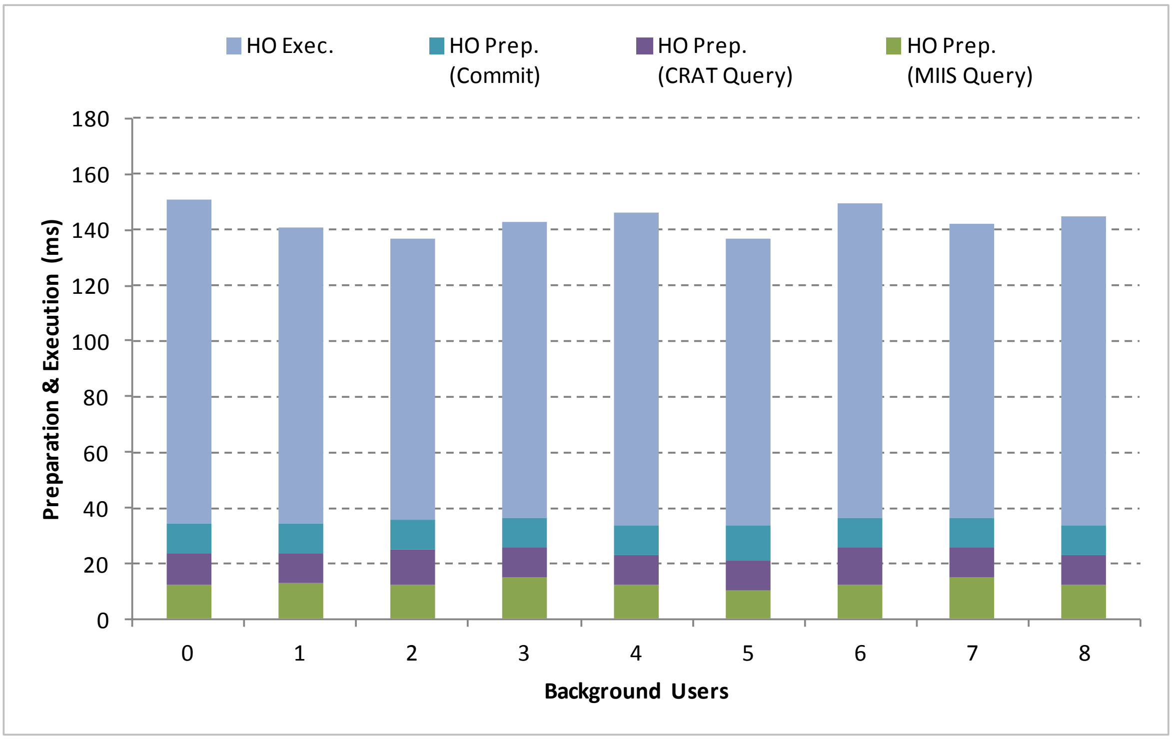

Figure 6-20: WiMAX to UMTS handover preparation and execution phases

6.5.2.2.3 UMTS to Wi-Fi Handover

The last handover is from the UMTS cell to the local Wi-Fi network. Succinctly, the user is still running the VoIP call service but he arrives into a public administration building which provides a Wi-Fi access network. As in the previous handover scenario from WiMAX to UMTS, the list of preferred ANs from the user indicates that the network operator must initiate a handover procedure from the serving UMTS cell to the Wi-Fi network. The measured values are shown in Figure 6-21.

From Figure 6-21, we can see that the handover preparation time is around 31 ms, independently of the background users' number. As in the WiMAX to UMTS handover scenario, illustrated in Figure 6-20, this value is significantly smaller than the 125 ms obtained for the handover preparation phase of the MIHO from Wi-Fi to WiMAX (Figure 6-19). The reason for this behavior is related with the fact that, in a NIHO scenario, the UMTS wireless link is not involved in the handover preparation phase, and therefore the internal steps will not be affected by the UMTS one-way delay (approximately 40 ms).

With respect to the handover execution time, also illustrated in Figure 6-21, it takes around 48 ms to complete, and is always constant. The handover execution time consuming reasons are similar to the ones depicted for the previous two handover scenarios.

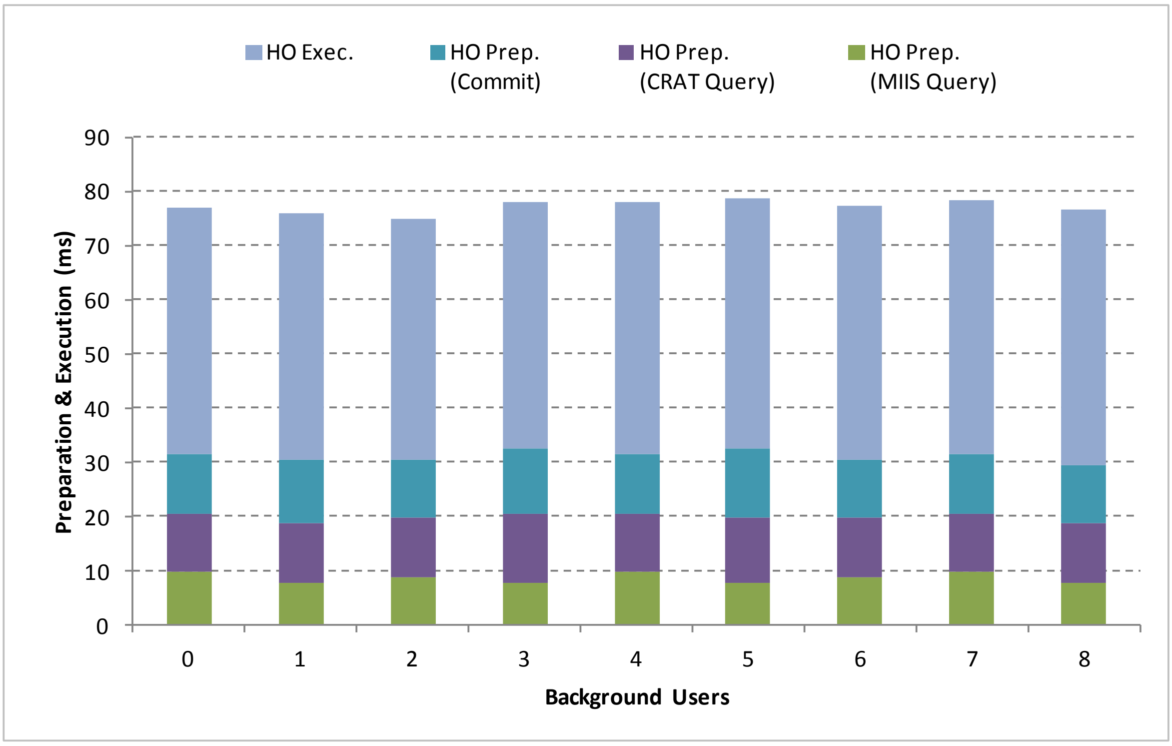

Figure 6-21: UMTS to Wi-Fi handover preparation and execution phases

6.5.3. Large-Scale Vertical Handover QoS Measurements

6.5.3.1. Simulated Scenario and Tests Methodology

On the previous subsection we have described the time spent on the handover preparation and execution phases. In this subsection we will provide results related with QoS measurements, specifically, packet delay, jitter and loss.

6.5.3.2. Results

Figure 6-22 and Figure 6-23 present the packet delay and packet jitter, respectively, for the three handover scenarios considered.

In the Wi-Fi to WiMAX handover scenario, the packet delay (one-way delay) is approximately 17 ms up to 6 background users, during handover. This value is the sum of the one-way delays of the wireless link (10 – 12 ms) and the wired link (5 – 10 ms). When the number of background users is more than 7, the Wi-Fi link saturates and the packet delay has an abrupt increase. The packet jitter has an identical behavior. Up to 3 users, the jitter is approximately 1.5 ms and constant. For 3 or more background users, it starts slightly increasing. For the WiMAX to UMTS handover scenario, the packet delay is approximately 38 ms and the packet jitter is 4.3 ms. In the last handover scenario, from UMTS to Wi-Fi, the packet delay and jitter are 54 ms and 6.3 ms, respectively. Both WiMAX to UMTS and UMTS to Wi-Fi handovers do not saturate the wireless channels, and therefore, the measured values are independent of the background users' increase.

Finally, while the wireless links are not saturated, the packet loss is approximately zero.

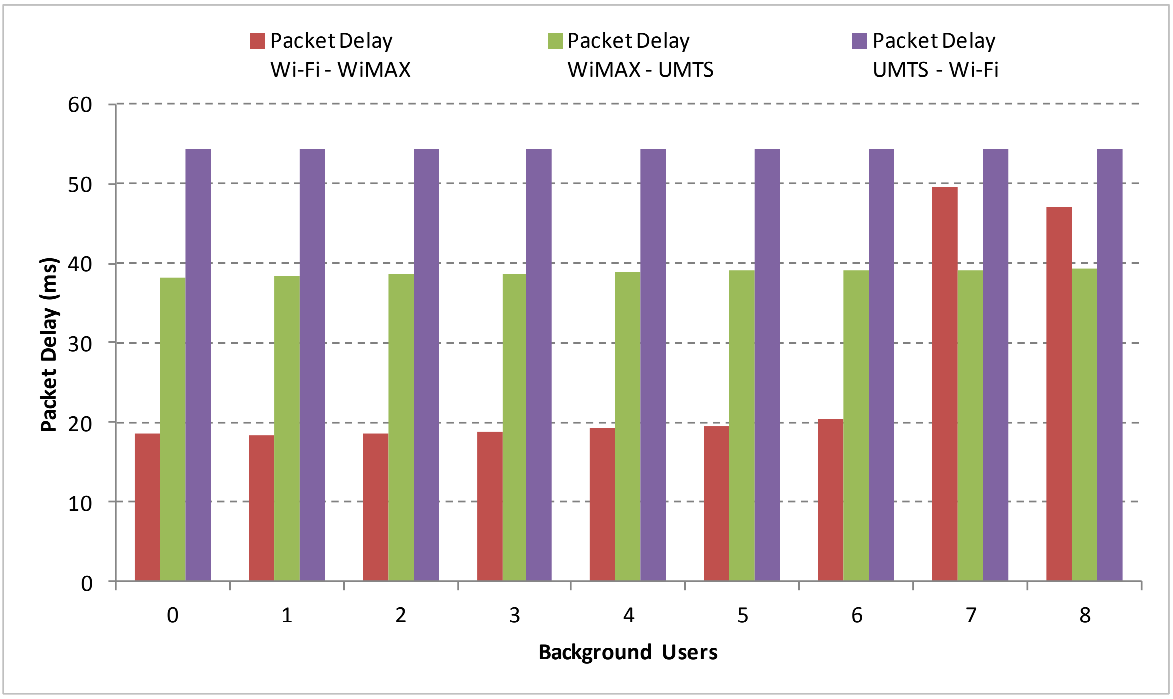

Figure 6-22: Packet delay

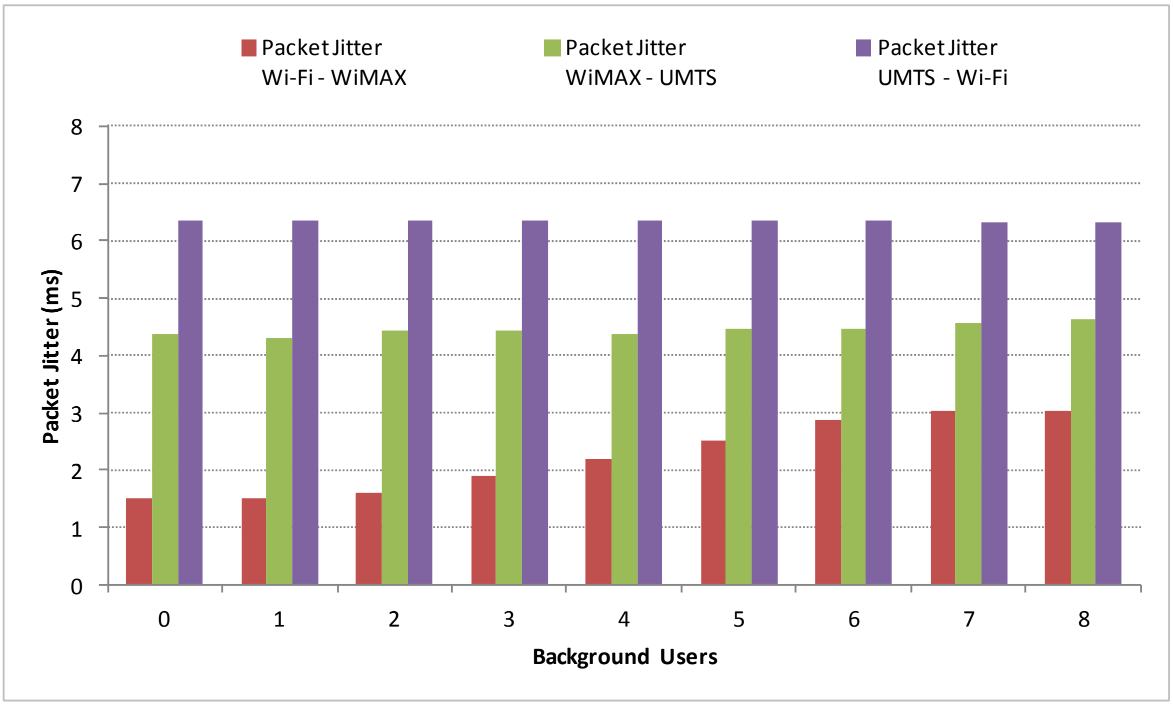

Figure 6-23: Packet jitter

6.6. Experimental Performance Evaluation

This section presents handover measurements performed in a heterogeneous wireless testbed composed by WiMAX, Wi-Fi and UMTS/HSPA (commercial) ANs. An Android-based smartphone was adapted and integrated as the demonstrator MN [197] [198]. The presented results depict a NIHO approach using the MIH framework to interact with entities involved in the mobility process. First, in section 6.6.1, the handover signaling results are depicted for each one of the handover phases, namely preparation, execution and completion. Special focus is given for the handover preparation internal sub-phases, including the neighbor ANs discovery (section 6.3.2.1), CANs resources availability check (section 6.3.2.2) and TANs resources reservation (section 6.3.2.4). Finally, in section 6.6.2, QoS performance metrics are also presented for three sets of services, namely FTP, Video and VoIP, to evaluate their behavior during a vertical handover procedure.

6.6.1. Experimental Optimized Vertical Handover Signaling Measurements

6.6.1.1. Implemented Demonstrator and Tests Methodology

Figure 6-24 illustrates the network topology of the experimental testbed. The testbed involves three different access technologies: commercial UMTS/HSPA, Wi-Fi and WiMAX. WiMAX is used to provide last mile connectivity to/from the Wi-Fi infrastructure.

The testbed is composed by a concatenated WiMAX/Wi-Fi AN and a UMTS/HSPA AN. The WiMAX/Wi-Fi AN is composed by a backhaul WiMAX BS and a SS from Redline Communications [208], which provides connectivity to a last-mile Wi-Fi AP from Cisco [209]. The WiMAX/Wi-Fi AN is connected to the CN through the ASN-GW, implemented in Linux Ubuntu. The ASN-GW contains the entities depicted in section 6.1, including the WXLM entity, which controls all the WiMAX network procedures, enabling the thorough analysis in an experimental environment of the radio resources provisioning impact, as described in section 6.2 [190] [191] [194]. Furthermore, the ASN-GW acts as an IEEE 802.21 PoS.

Besides the WiMAX/Wi-Fi concatenated AN, the demonstrator also includes a UMTS/HSPA HSPA commercial network from the PT Group mobile operator, also known as TMN [210]. The UMTS/HSPA mobile network is composed by several NBs, RNCs, Serving GPRS Support Nodes (SGSNs) and one Gateway GPRS Support Node (GGSN). The connection between the CN and the UMTS/HSPA mobile network is made through the UMTS/HSPA GW, implemented in Linux Ubuntu, which acts as the UMTS/HSPA network controller and the IEEE 802.21 PoS.

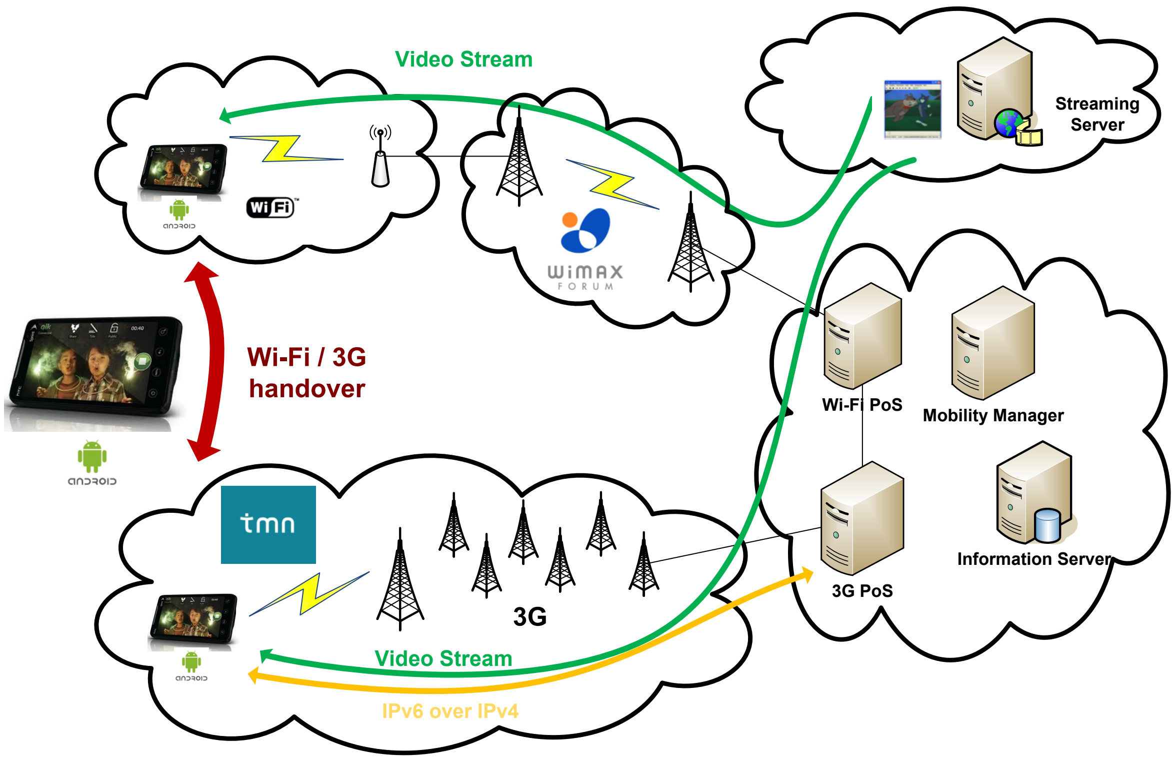

Figure 6-24: Inter-technology mobility experimental scenario

Since the testbed is based on IPv6 and the UMTS/HSPA commercial network does not support IPv6, a tunnel is created between the UMTS/HSPA GW and the MN to transport the IPv6 datagrams over the IPv4 network (IPv6-in-IPv4 tunneling). This tunnel affects the handover time due to the need for further processing by the entities involved in the communication, since they have to encapsulate/decapsulate an extra header from the IP packet. Another limitation related with the UMTS/HSPA commercial network is the resources reservation procedures. While in the WiMAX/Wi-Fi AN it is possible to control the SF reservation procedures, the UMTS/HSPA network does not provide any type of interface to control the PDP context activation procedures. Therefore, it is not possible to provide QoS guarantees on the UMTS/HSPA AN.

The CN includes the NMM, the MIP HA, the IEEE 802.21 IS, the AAA and DHCP servers, as well as a Real Time Streaming Protocol (RTSP) [211] server, more precisely the Darwin Streaming Server [212], carrying video traffic (128 Kbps and 256 Kbps) over the Real Time Protocol (RTP) [213]. One-way delay, packet loss, throughput and jitter QoS metrics were obtained to evaluate the handover performance.

Furthermore, the CN also contains the Distributed Internet Traffic Generator (D-ITG) server [214] to generate/emulate traffic for the performance measurements. VoIP (G722.1 codec), FTP and video traffic (simulates a real RTSP session with a variable rate of RTP packets) were generated. Signaling (handover initiation, preparation, execution and completion) and QoS metrics were obtained (one-way delay, packet loss, throughput and jitter), as presented in section 6.6.1.2 and section 6.6.2.2, respectively. The CN entities run on Linux Ubuntu.

The mobility management protocol implementation used was the USAGI-patched Mobile IPv6 for Linux (UMIP) [215], which is an open-source implementation of the MIPv6 protocol. The normal operation of MIPv6 does not allow a seamless handover because it only switches to another network when the current network interface disconnects (e.g. stop receiving *MIPv6 Router Advertisements*). The UMIP version in use was modified to allow a make-before-break handover, with the two interfaces connected, reducing the packet loss during the handover. Thus, the current implementation is able to receive commands from other entities in order to obtain the current network interface in use and, if required, trigger the handover to a specific interface.

On the client side is an Android [216] smartphone, more precisely an HTC Google Nexus One [217] with a modified version of the Android platform, version 2.1 and kernel Linux 2.6.32 with IPv6, mobility and tunneling support enabled. The Android terminal is running the TMM, MIP FA client, 802.21 MIHF and the MN XLM, as described in section 6.1. The video streaming is received by a RTSP client application, with buttons to control the playback and the video quality. The client version of the D-ITG tool is also running on the MN. The entities involved on the demonstrated are described in Table 6-11.

Table 6-11: Testbed components

Name	Hardware	Operating System	Software Modules
Mobility Decision Entity (MDE)	PC	Ubuntu 9.0.4 (kernel 2.6.30)	MIP TMM 802.21 MIHF IS Database
Correspondent Node	PC	Ubuntu 9.0.4 (kernel 2.6.30)	Darwin Streaming Server D-ITG Server MIP
UMTS/HSPA Gateway	PC	Ubuntu 9.0.4 (kernel 2.6.30)	UMTS/HSPA RM 802.21 MIHF
WiMAX ASN-GW	PC	Ubuntu 9.0.4 (kernel 2.6.30)	WXLM 802.21 MIHF
Android Mobile Node	HTC Google Nexus One	Android OS 2.1 (kernel 2.6.32)	TMM MIPv6 D-ITG Client 802.21 MIHF XLM

In what concerns the tests methodology, the MN MIHF registers on the network MIHF; thereafter the NMM subscribes to the MN events and configures the signal thresholds. Thereafter the video traffic is sent from the server (either D-ITG or Darwin) to the current location of the MN (either UMTS/HSPA or Wi-Fi terminal interface). When the signal threshold is exceeded, the NMM initiates the handover preparation procedures, including the radio resources provisioning on the TAN, and connects the terminal to the TAN. After the handover is executed, the NMM disconnects the data connectivity on the PAN and releases the reserved resources.

To ensure solid results we made 20 handovers for each test, 10 from UMTS/HSPA to WiMAX/Wi-Fi and 10 from WiMAX/Wi-Fi to UMTS/HSPA HSPA. Every run lasts six seconds, with the handover occurring approximately at half of that time period.

6.6.1.2. Results

6.6.1.2.1 Handover Configuration Phase

This phase configures all the IEEE 802.21 procedures for the handover management. All the tasks related with this phase are made on the bootstrapping period and therefore are prior to the terminal mobility process. As detailed in section 6.3.1, after registering on the network side MIHF, the NMM, acting as an MIH user, triggers the discover capability process to detect the supported capabilities of the MN link layers (UMTS/HSPA and Wi-Fi) through the *MIH_Capability_Discovery* mechanism. Thereafter, based on the discovered capabilities, the NMM subscribes the IEEE 802.21 events using the *MIH_Event_Subscribe* mechanism and configures the radio signal thresholds using the IEEE 802.21 *MIH_Configure_Thresholds* mechanism.

Figure 6-25 illustrates the time required for configuring the UMTS/HSPA and Wi-Fi interfaces, as described above. The factor with a major impact on this phase is the packet delay caused by the UMTS/HSPA and Wi-Fi wireless access links. Six messages are exchanged between the NMM and the MN in this phase: *MIH_Capability_Discovery Req/Rsp*, *MIH_Event_Subscribe Req/Rsp* and *MIH_Configure_Threshold Req/Rsp*, illustrated in *blue*, *yellow* and *green* color bars in Figure 6-25, respectively. For the UMTS/HSPA scenario, it takes approximately 800 ms to finalize the three IEEE 802.21 mechanisms for the MN configuration, whereas in the Wi-Fi it takes about 40 % less of the UMTS/HSPA time, or 500 ms, to complete the terminal configuration procedures.

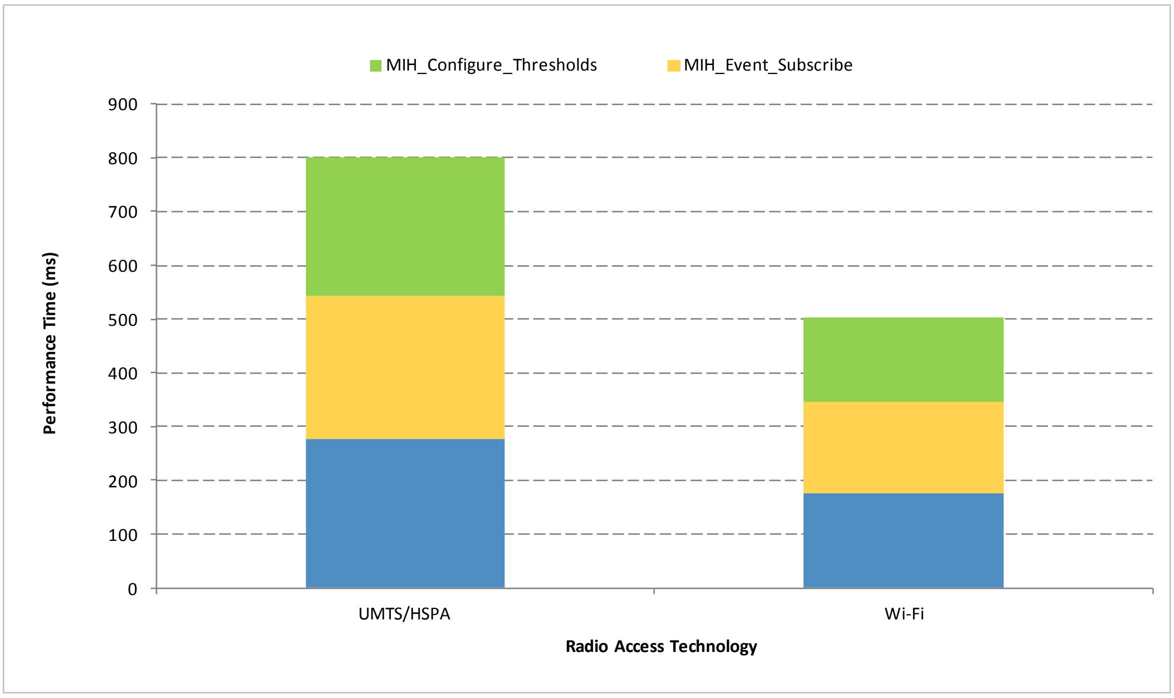

Figure 6-25: Handover configuration management phase

6.6.1.2.2 Handover Preparation Phase

During the handover preparation phase the candidate networks have to be queried about their resources availability, the target network has to be selected and thereafter prepared to receive the MN in a very short period of time. This phase is critical for the handover success and therefore measurements were made for each one of its internal sub-phases: neighbor AN discovery (section 6.3.2.1), CAN resources availability check (section 6.3.2.2) and TAN resources reservation (section 6.3.2.4).

Figure 6-26 and Figure 6-27 illustrate the handover preparation phase measurements for Wi-Fi/WiMAX to UMTS/HSPA and UMTS/HSPA to Wi-Fi/WiMAX handovers, respectively. The first sub-phase of the handover preparation – neighbor AN discovery (*blue*) sub-phase, takes approximately 105 ms – 115 ms for all service types (IPTV, VoIP and HTTP) and for both handover types. This sub-phase is triggered when the NMM detects that the SAN wireless link conditions are weakening, and therefore it is necessary to search for a neighbor AN. The NMM queries the IEEE 802.21 IS database for the neighboring networks through the *MIH_Get_Information* mechanism. The IS returns a UMTS/HSPA network available in the MN surrounding area for the Wi-Fi/WiMAX to UMTS/HSPA handover case or a Wi-Fi network for the UMTS/HSPA to Wi-Fi/WiMAX handover scenario.

The next step is to confirm that the AN retrieved by the IS is reachable by the MN. Therefore the AN scanning sub-phase is initiated by the NMM through the *MIH_Link_Actions (SCAN)* mechanism, as described in section 6.3.2.2. In the developed tests, only the Wi-Fi wireless interface was possible to scan due to access restrictions to the UMTS/HSPA scanning primitive on the Android smartphone. Therefore the scanning sub-phase was only measured on the UMTS/HSPA to Wi-Fi/WiMAX handover, as illustrated in Figure 6-27 (*yellow*). The Wi-Fi interface scan took approximately 275 ms, including the *MIH_Link_Actions (SCAN)* mechanism primitives exchange between the NMM and the MN on the SAN (UMTS/HSPA AN), as well as the time required by the Wi-Fi interface on the smartphone to perform the scan. Although very important for the handover procedure, the Wi-Fi scan sub-phase is very time-consuming, taking around 60 % of the UMTS/HSPA to Wi-Fi/WiMAX handover preparation phase.

Thereafter the CAN resources availability check sub-phase (*green*) is initiated by the NMM and takes approximately 20 ms for both handover types. During this sub-phase the NMM queries the CAN (either UMTS/HSPA or Wi-Fi/WiMAX) RM for the resources availability using the *MIH_N2N_HO_Query_Resources* mechanism. Since there was no access to the commercial UMTS/HSPA AN entities to check for resources availability, this procedure was emulated in the UMTS/HSPA GW and therefore the time consumed for this phase (approximately 20 ms) is composed by the *MIH_N2N_HO_Query_Resources* mechanism primitives exchange between the NMM and the RM plus an estimation of the time required by the RM to retrieve the UMTS/HSPA AN resources availability.

Finally, before executing the handover from the SAN to the TAN, the TAN resources reservation sub-phase (*violet*) is triggered. During this phase the NMM communicates with the TAN (either UMTS/HSPA or Wi-Fi/WiMAX) RM using the *MIH_N2N_HO_Commit* mechanism to reserve the required resources on the access technology. For the UMTS/HSPA to Wi-Fi/WiMAX handover, a dedicated WiMAX SF is created, whereas for the Wi-Fi/WiMAX to UMTS/HSPA handover scenario, a dedicated PDP context on the UMTS/HSPA AN is established. For both handover scenarios, the RM enforces the resources reservation decision on the access technology through the proposed *MIH_Link_Actions (QOS_RESERVATION)* mechanism. For the UMTS/HSPA case, this sub-phase is very time-consuming and took around 360 ms. Nevertheless, as in the previous sub-phase, since there was no access to the commercial UMTS/HSPA AN reservation control entities to activate the PDP context, this procedure was emulated on the UMTS/HSPA GW. For the Wi-Fi/WiMAX case, this sub-phase was significantly shorter, taking around 22 ms, which is 90 % less compared to the UMTS/HSPA case. Furthermore, it is important to highlight that this time includes the *MIH_N2N_HO_Commit* mechanism between the NMM and the Wi-Fi/WiMAX RM, the *MIH_Link_Actions (QOS_RESERVATION)* mechanism between the Wi-Fi/WiMAX RM and the WXLM, as well as the required time by the WXLM and the WiMAX BS to establish the SF on the radio link (including the SNMP messages between the WXLM and the WiMAX BS from Redline Communications).

To sum up, the complete preparation phase takes approximately 500 ms – 550 ms for both handover types. Although the preparation time is similar, the reason is different for each handover scenario. For the Wi-Fi/WiMAX to UMTS/HSPA handover case, this time is due to the resources reservation procedure, which takes around 360 ms. Regarding the UMTS/HSPA to Wi-Fi/WiMAX handover case, the preparation time is mostly due to the Wi-Fi scanning procedures and the IEEE 802.21 signaling messages traversing the UMTS/HSPA wireless link, which takes approximately 250 ms.

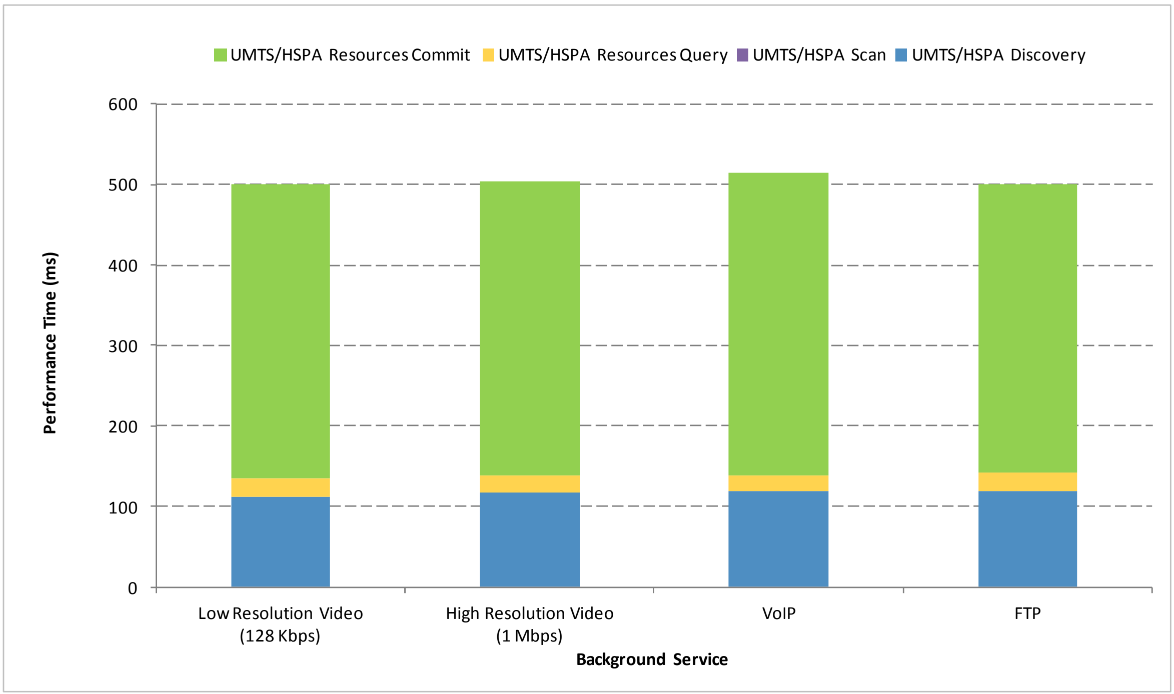

Figure 6-26: Wi-Fi/WiMAX to UMTS/HSPA handover preparation phase

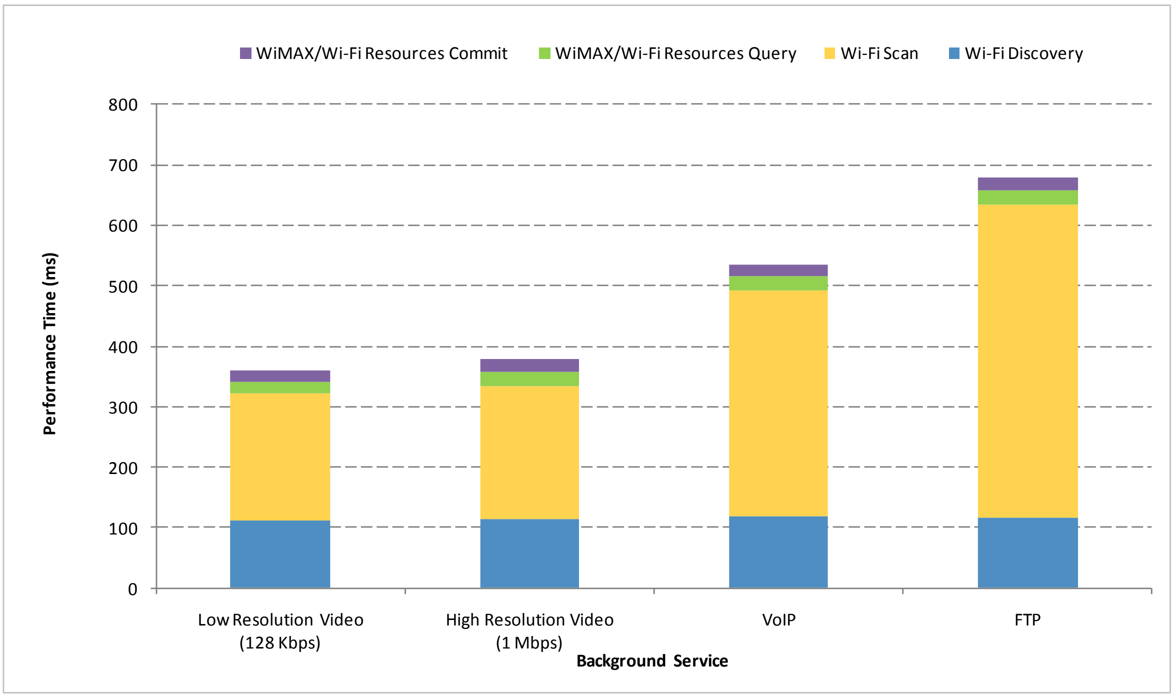

Figure 6-27: UMTS/HSPA to Wi-Fi/WiMAX handover preparation phase

Comparing the UMTS/HSPA to WiMAX/Wi-Fi testbed results presented above with the simulation results described in section 6.5.2.2.3, it was verified that the handover preparation time is substantially higher in testbed scenario. In total, the handover preparation time using the simulator is about 30 ms, whereas the time obtained for the demonstrator is close to 350 ms. This difference is justified as follows:

- Discovery of neighboring ANs (simulation = 10 ms vs. testbed = 110 ms): this difference is mainly due to the significant delay imposed by the access, search and return of the neighbor access network from the IS database. For the tests developed with the simulator, the information of neighboring networks is stored in a simple table and therefore is much simpler to read, taking thereby less time;
- Wi-Fi network scan (simulator = 0 ms vs. testbed = 275 ms): for the results obtained with the simulator, since the Wi-Fi interface was always up and accessible, this phase was not necessary. In the testbed case, for energy efficiency reasons, the Wi-Fi interface from the Android smartphone was switched off, and as such it was necessary to turn the interface on, scan the Wi-Fi frequency and provide the result to the NMM.

6.6.1.2.3 Handover Execution Phase

To capture and understand the behavior of the handover process during the execution phase, described in section 6.3.3, both the handover execution delay and the handover delay metrics were measured. While the former metric reflects the amount of time between sending the *MIPv6 Binding Update* and receive the first data packet in the new network interface, the later reflects the amount of time between the last packet received on the previous network interface and the first packet received on the new network interface. In practice, the handover execution delay represents the time that MIPv6 takes to update its new location and receive data on the new network interface.

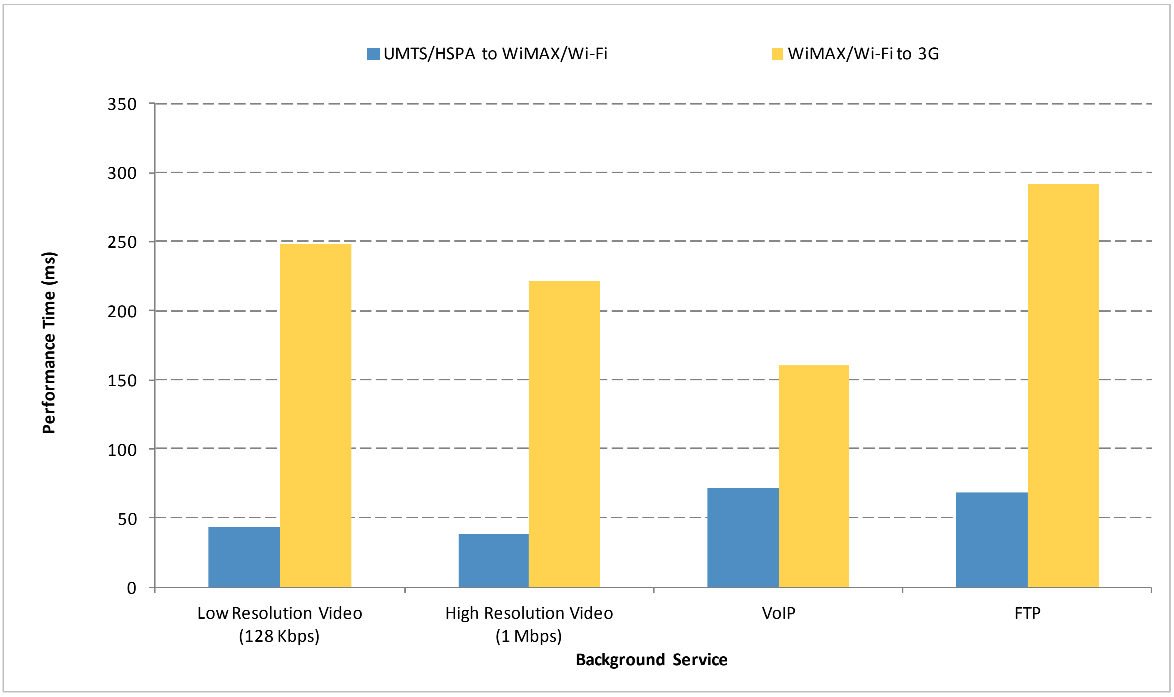

Figure 6-28: Handover execution delay

As presented in Figure 6-28, the handover execution delay difference between the two handovers is caused by the discrepancy between the packet delay when crossing each one of the involved access technologies. In the present experimental scenario, this value is lower from UMTS/HSPA to Wi-Fi because the *MIPv6 Binding Update* and the first packet received are exchanged in the new interface (Wi-Fi), which has a lower packet delay. This is due to the characteristics of the current UMTS/HSPA public network, which is usually under high traffic, loads and incurs in routes with a larger number of hops. Similarly, the handover delay difference is also caused by the discrepancy between the packet delay of the two technologies (see Figure 6-29), i.e. the latency of the first packet to arrive to the UMTS/HSPA interface is higher.

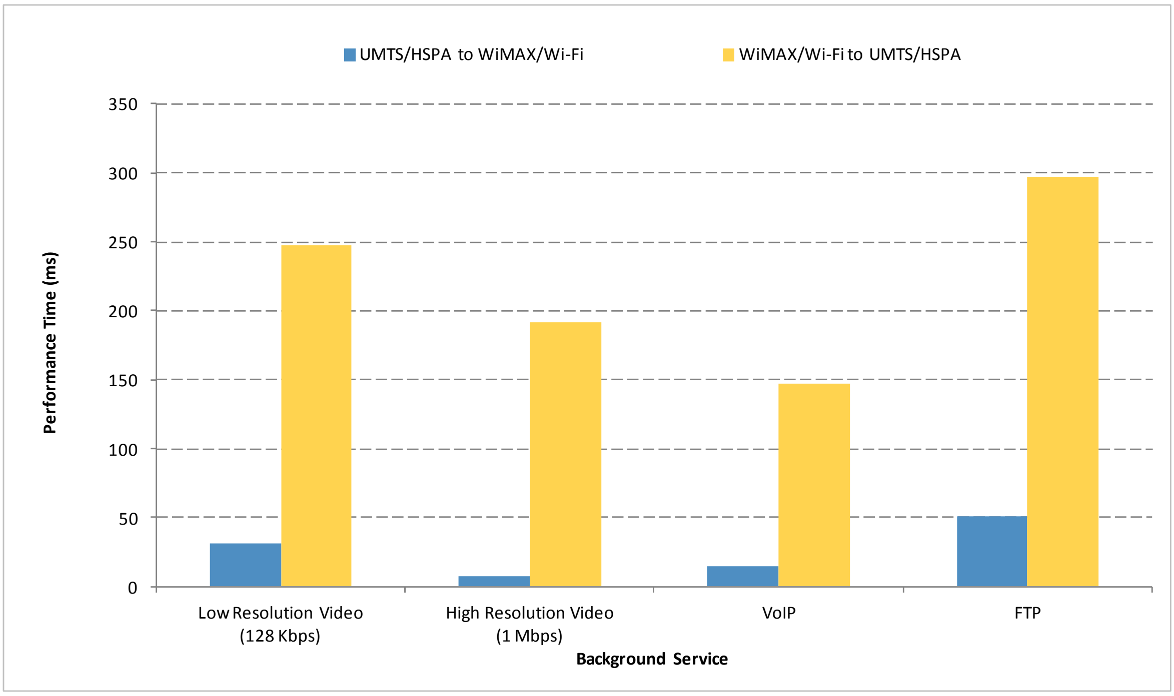

Figure 6-29: Handover delay

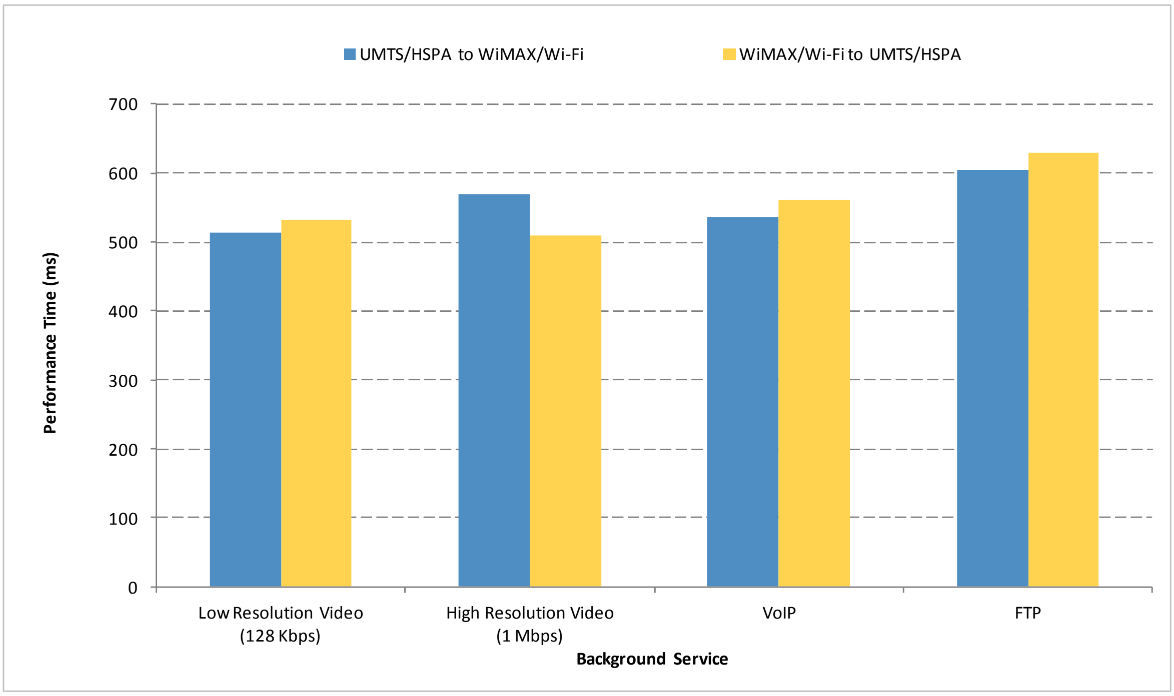

Figure 6-30: Handover execution phase

Besides the handover execution delay and the handover delay metrics described above, the handover execution phase can also be evaluated through the handover execution time, as described in section 6.3.3. The NMM initiates the handover execution phase by sending a *MIH_Net_HO_Commit Req* primitive towards the TMM. After the reception of this message, the TMM interacts with the MIPv6 client to trigger the *MIPv6 Binding Update* message. When the handover is finished, a *MIPv6 Binding Acknowledgement* message is sent by the HA towards the MN indicating that the handover is completed. As a result, the TMM triggers the *MIH_Net_HO_Commit Rsp* primitive towards the NMM indicating that the handover process is terminated. The period of time measured by the NMM from the moment that the *MIH_Net_HO_Commit Req* message is sent and the reception of the corresponding reply is the handover execution time.

Figure 6-30 illustrates the handover execution time for both handover types. As one can see, the handover execution time difference between these two types of handovers (UMTS/HSPA to Wi-Fi/WiMAX and Wi-Fi/WiMAX to UMTS/HSPA) is not significant because in this phase only two MIH messages are exchanged: one in the previous network and another in the selected network for handover. Thus, the impact of the UMTS/HSPA is not a differentiable issue in this phase.

Comparing the UMTS/HSPA to WiMAX/Wi-Fi testbed results presented above with the simulation results described in section 6.5.3.2, it was verified that they are very similar (simulation = 45 m vs. testbed = 35 ms).

6.6.1.2.4 Handover Completion Phase

Finally, after the handover to the new wireless interface is made, the resources on the PAN must be deleted. This is known as the handover completion phase, depicted in section 6.3.4. In this phase the NMM triggers the resources deletion in the previous access link (either UMTS/HSPA or Wi-Fi/WiMAX) by using the *MIH_N2N_HO_Complete* mechanism towards the PAN RM. For the UMTS/HSPA to Wi-Fi/WiMAX handover, the dedicated WiMAX SF is deleted, whereas for the Wi-Fi/WiMAX to UMTS/HSPA handover scenario, the dedicated PDP context on the UMTS/HSPA AN is removed. For both handover scenarios, the RM enforces the resources deletion decision on the access technology through the proposed *MIH_Link_Actions (QOS_DELETION)* mechanism.

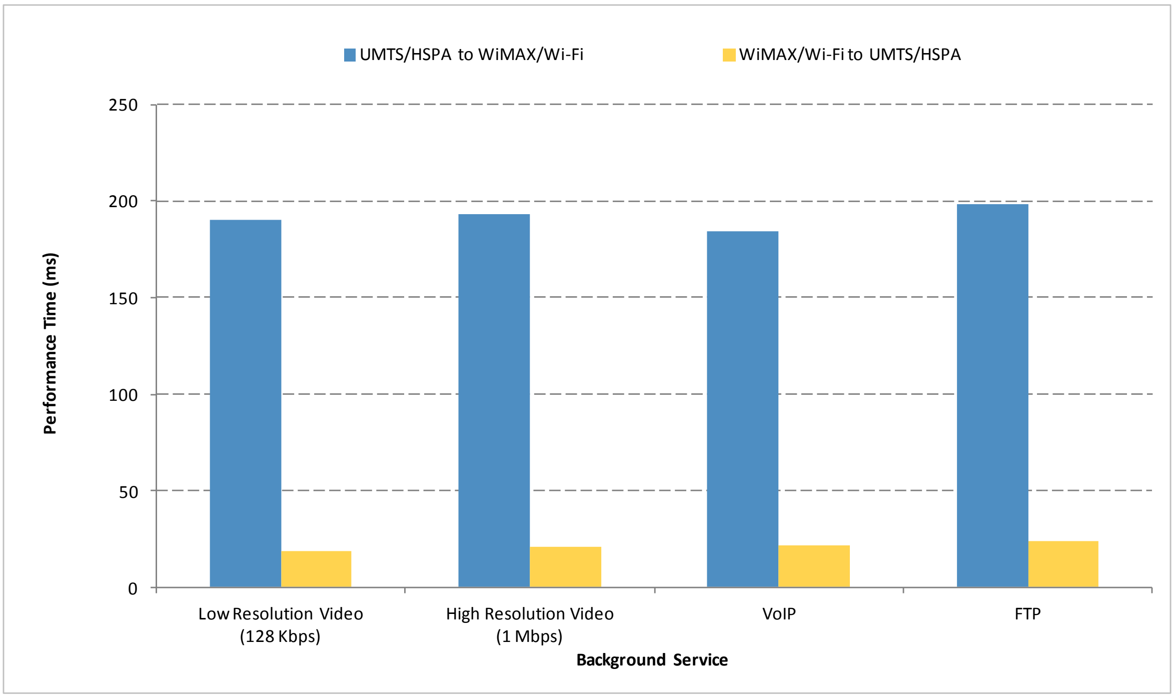

Figure 6-31: Handover completion phase

For the UMTS/HSPA case, this phase is very time-consuming and took around 190 ms. Nevertheless, since there was no access to the commercial UMTS/HSPA AN reservation control entities to delete the PDP context, this procedure was emulated on the UMTS/HSPA GW. For the Wi-Fi/WiMAX case, this phase was significantly shorter, taking around 20 ms. Furthermore, it is important to highlight that this time includes the *MIH_N2N_HO_Complete* mechanism between the NMM and the Wi-Fi/WiMAX RM, the *MIH_Link_Actions (QOS_DELETION)* mechanism between the Wi-Fi/WiMAX RM and the WXLM, as well as the required time by the WXLM and the WiMAX BS to remove the SF on the radio link (including the SNMP messages between the WXLM and the WiMAX BS from Redline Communications).

6.6.2. Experimental Vertical Handover QoS Measurements

6.6.2.1. Implemented Demonstrator and Tests Methodology

In this sub-section are illustrated and described a set of QoS measurements during the handover procedure between Wi-Fi and UMTS/HSPA. More precisely, the following metrics are discussed: throughput, jitter, packet loss and delay.

6.6.2.2. Results

6.6.2.2.1 Packet Throughput

Figure 6-32 and Figure 6-33 illustrate the throughput measurements during the handover procedure. Note that the throughput for the Wi-Fi/WiMAX to UMTS/HSPA handover has a downward spike for the higher bitrates (High Resolution Video – 1 Mbps). The reason for this behavior is because the TAN is the UMTS/HSPA AN. Since this is a commercial UMTS/HSPA network and therefore there was no resources control in this network, it is not possible to make any IEEE 802.21 resources reservation prior to the handover (as specified in section 6.3.2.4). Hence, after the transition from Wi-Fi/WiMAX to UMTS/HSPA, the throughput decreases dramatically once the UMTS/HSPA network is unable to satisfy the access to such high throughputs so fast. After receiving the first packets, the UMTS/HSPA network entities automatically start the resources reservation procedures dynamically, guaranteeing the required throughput.

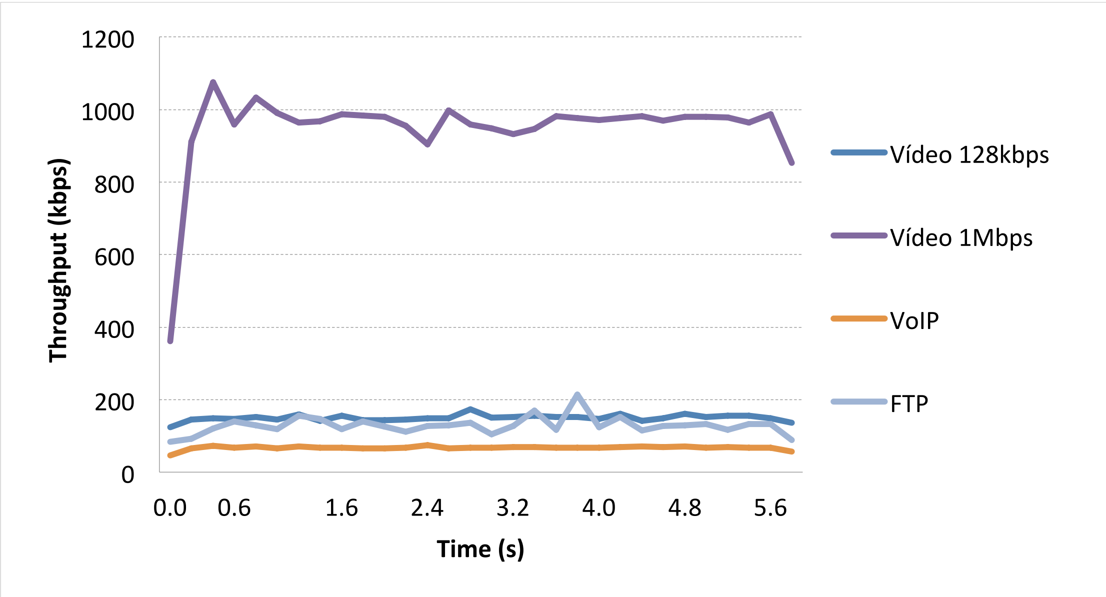

Figure 6-32: UMTS/HSPA to Wi-Fi/WiMAX handover throughput QoS metric

Although the throughput decreases immediately after the handover, the sender continues to send the data packets at the same rate. The receiver, in this case UMTS/HSPA, stores the incoming packets in an internal buffer until the radio link is prepared. As a result, as soon as the UMTS/HSPA radio link is prepared, a burst of packets is sent towards the receiver to compensate for the throughput decline. This behavior is observable through the ascending peak present in Figure 6-33.

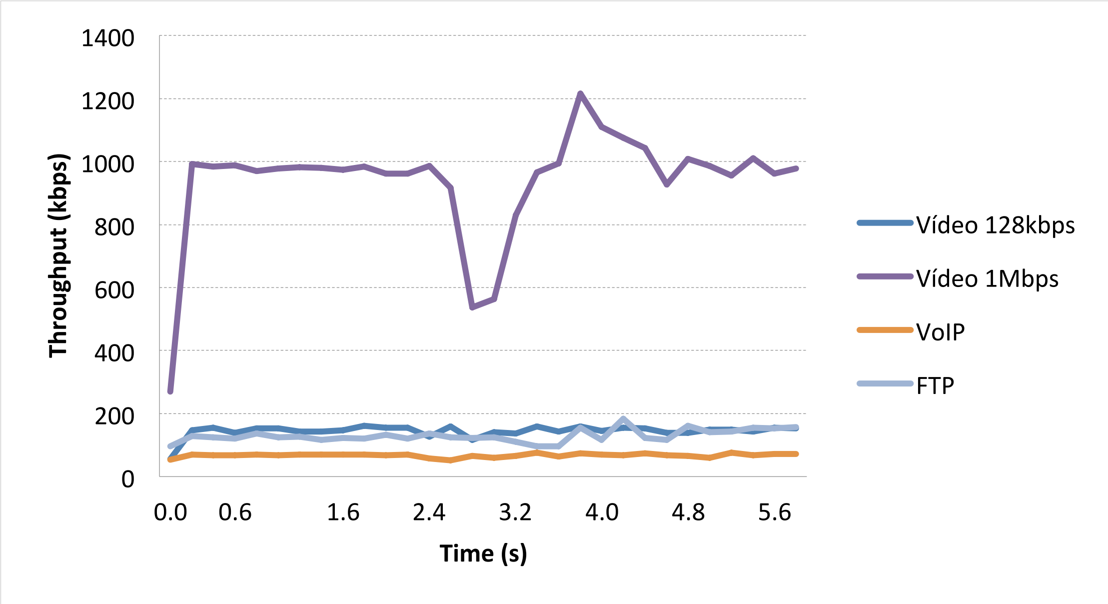

Figure 6-33: Wi-Fi/WiMAX to UMTS/HSPA handover throughput QoS metric

6.6.2.2.2 One-way Delay

Figure 6-34 and Figure 6-35 illustrate the delay measurements during the UMTS/HSPA and Wi-Fi/WiMAX handover procedures.

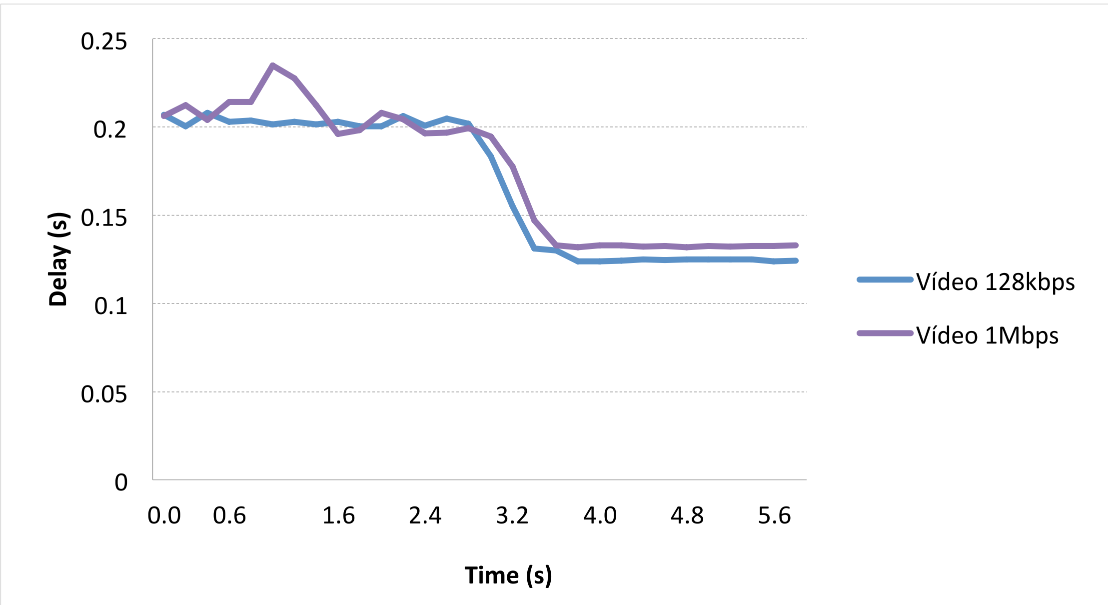

Figure 6-34: UMTS/HSPA to Wi-Fi/WiMAX handover delay QoS metric (video services)

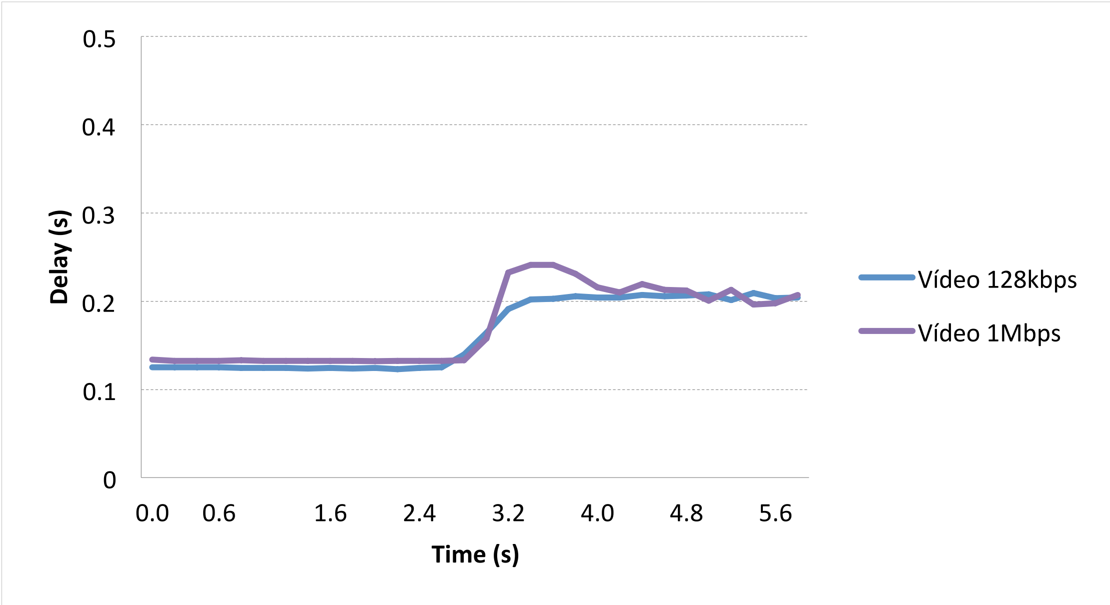

Figure 6-35: Wi-Fi/WiMAX to UMTS/HSPA handover delay QoS metric (video services)

As expected, the delay in both types of video traffic is higher for UMTS/HSPA, and we can easily distinguish the moment of the handover execution.

6.6.2.2.3 Packet Jitter

Figure 6-36 and Figure 6-37 present the packet jitter for the UMTS/HSPA to WiMAX/Wi-Fi and WiMAX/Wi-Fi to UMTS/HSPA handovers, respectively. Since the results are similar for the several types of services, only the Video and VoIP services are illustrated on the following figures.

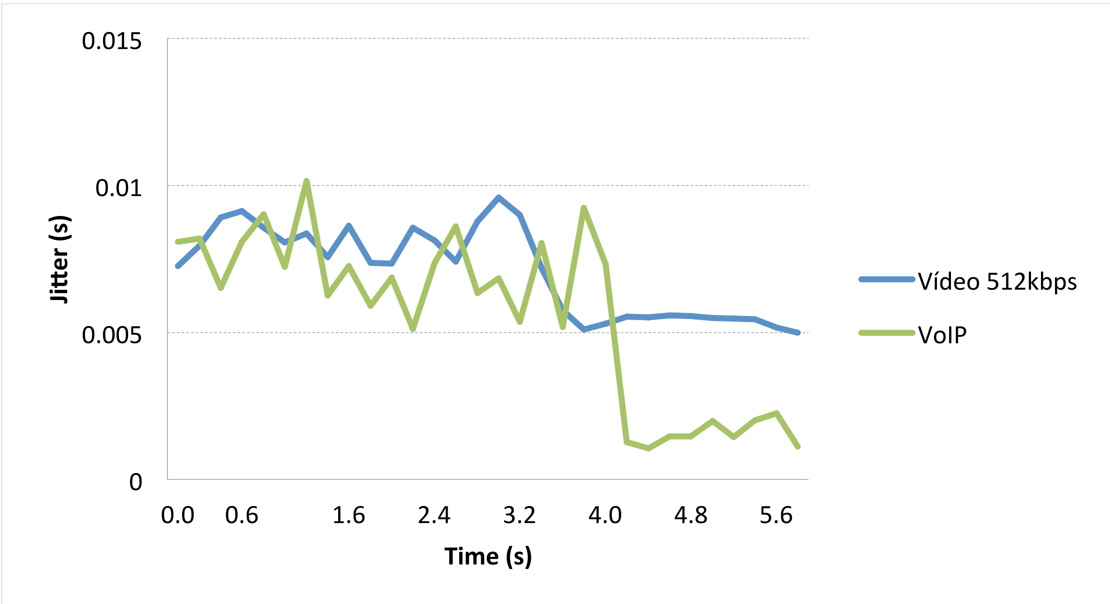

Figure 6-36: UMTS/HSPA to Wi-Fi/WiMAX handover jitter QoS metric

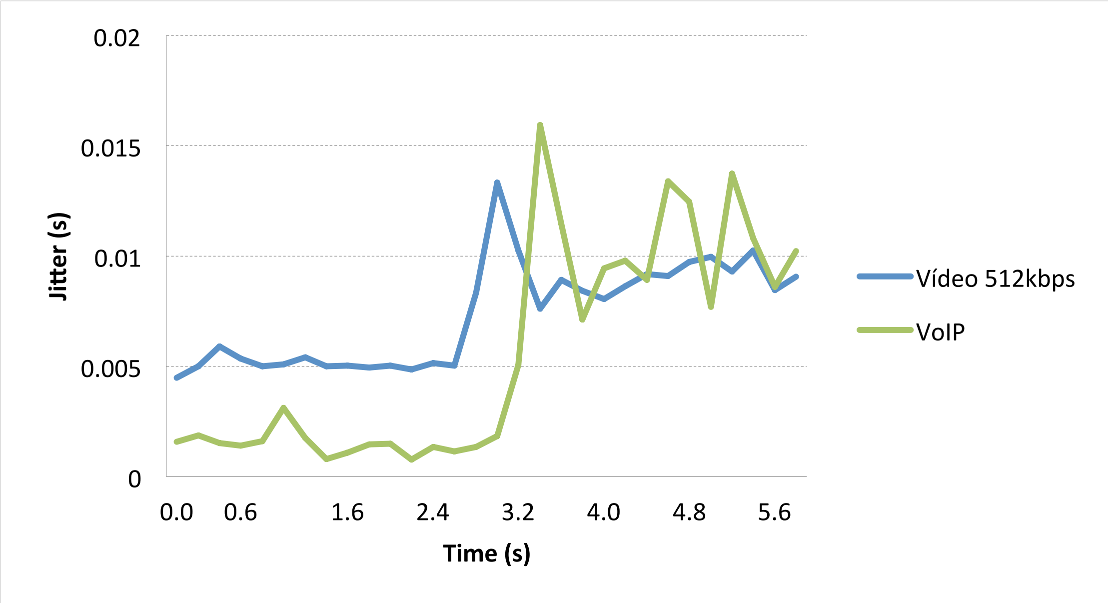

Figure 6-37: Wi-Fi/WiMAX to UMTS/HSPA handover jitter QoS metric

For the WiMAX/Wi-Fi to UMTS/HSPA handover scenario, it should be highlighted an instant increase on the jitter value after the handover. This event is due to the fact that a handover is made from a network with less delay (WiMAX/Wi-Fi) to another network (UMTS/HSPA) with a higher delay. Thus, since the jitter is the time between the reception of two packets, after the handover there is always a higher jitter within the first packets received. Thereafter the jitter value stabilizes.

6.6.2.2.4 Packet Loss

Figure 6-38 depicts the packet loss during the handover execution procedure.

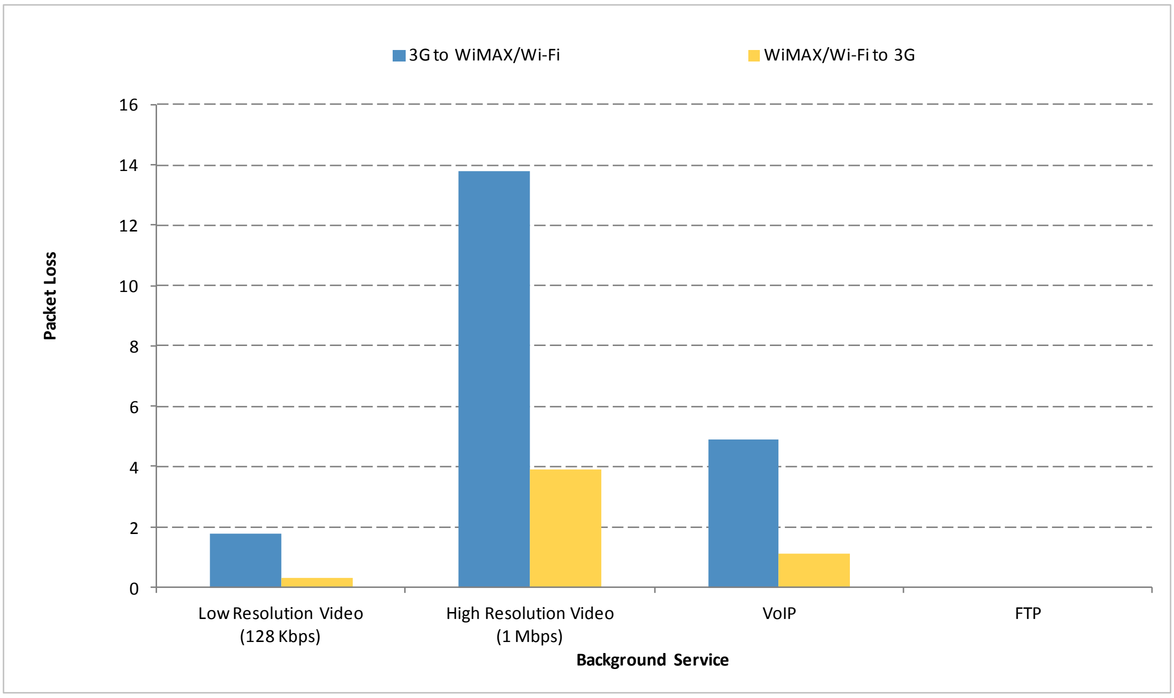

Figure 6-38: Wi-Fi/WiMAX to/from UMTS/HSPA handover packet loss QoS metric

Since both wireless interfaces are active during the handover execution, the losses are mainly out of order packets caused by the significant delay given by the UMTS/HSPA network. Since the UMTS/HSPA network has a high one-way delay, when the handover execution is triggered (by the *MIPv6 Binding Update* message from the MN towards the MIPv6 HA), some data packets are already traversing the UMTS/HSPA network, and new data packets arriving at the MIPv6 HA are redirected through the Wi-Fi network. Since the delay in UMTS/HSPA is higher then in Wi-Fi, the data packets sent through Wi-Fi will arrive first to the MN – although they were sent after the data packets from the UMTS/HSPA network. This will cause the MN to receive out-of-order packets, and therefore, at the application level, these packets are lost.

6.7. Summary

This chapter proposed a mobility heterogeneous architecture, comprising Wi-Fi, WiMAX, UMTS/HSPA and LTE ANs. The architecture supports mobility procedures through MIP, and is further extended to support IEEE 802.21 services. Handover decisions are made by the NMM and/or the TMM entities, which directly interact with the mobility management protocol to enforce mobility decisions. By incorporating optimized handover functionalities through IEEE 802.21, a MN has the potential to perform seamless handovers between heterogeneous access technologies. The optimized handover framework is able to support multi-homing, network and mobile initiated handovers, as well as integration of QoS procedures and mobility functions providing minimum service disruption. Its key features are the practical approach regarding implementation and the consideration of resource query, resource reservation and power management that are not currently covered by the IEEE 802.21 standard.

Two main alternatives emerge as possible architectural choices for future implementations. These are (i) the PoA/PoS and (ii) the non-PoA/PoS approaches. The two different approaches deal with the location of PoS functionality in the network. The PoA/PoS approach is more straightforward concerning complexity since all critical MIH operations (PoS and PoA) are located in the same network node. This means that the AP or the BS is in full control of the handover process, and MIH messages concerning link layer functionality (e.g. for resource management at layer 2) are directly applied without inter-MIH communication. On the other hand, the non-PoA/PoS approach assumes different locations for the PoS and the PoA, which makes it necessary to either transport MIH messages between them or use standard functionality of underlying technologies for performing critical operations such as resource management.

Other criteria for favoring one of the two architectures are implementation and security. The non-PoA/PoS approach is targeted at more “closed” systems where operators are totally in charge of the traffic in their networks and the control of the handover process is closer to the core network nodes. By placing the PoS functionality in the ASN-GW or the Wi-Fi GW also makes the network more secure and less vulnerable to attacks than placing such functionality in an AP (PoA/PoS approach). Moreover, scalability and availability dictate to enhance more powerful machines with PoS functionality rather than cheaper and often faulty network nodes.

Apart from the aforementioned issues, other open areas include the way information at the IEEE 802.21 IS database is updated and energy efficiency in multi-radio devices. In our study, we have assumed that PoA locations are already known at the IS. However, if information update is needed, a mechanism performing update on a periodical basis could be used. Concerning power-saving, one solution is to always switch unused network interfaces off. This has been followed in the proposed handover procedure where the old interface is disabled right after the handover completion. In case of multiple candidate networks and in order to minimize power consumption, any unnecessary interfaces powered-on for scanning could be powered-off immediately after network selection. Another possible alternative for energy-efficient use of the wireless interfaces could be to simply keep them in power-save mode when not used.

IEEE 802.21 does not cover the radio resources management in the ANs during the seamless handover procedures. This chapter also described a method for managing radio resources in the radio access technologies during a handover procedure by proposing new command primitives for the IEEE 802.21 framework. The proposed IEEE 802.21 primitives allow an application level entity, such as a RM, to enforce radio resources allocation and deletion in the access technologies, either locally or remotely, as well as to receive event notifications from the link layer technologies with the resources reservation and/or deletion result.

Furthermore, a technology independent, IEEE 802.21-based seamless handover mechanism was described in this chapter. Moreover, it was also described the missing description regarding the integration of the IEEE 802.21 functionalities, more precisely the generic lower layer interface MIH_LINK_SAP with the radio access technologies specific procedures and interfaces. For the WiMAX access technology case, the translation procedures are performed on the WXLM. The integration of media-dependent interfaces within the MIHF facilitates the adoption of the IEEE 802.21 standard by the access technologies standardization bodies.

To validate the described mechanisms in a large-scale environment, we have created an heterogeneous network access scenario in the NS-2 tool comprising WiMAX, Wi-Fi and UMTS/HSPA access technologies. Additionally, a deep analysis of NS-2 simulator was performed, and several modifications were made to support the envisioned mechanisms and scenarios. Specifically, important add-ons to the IEEE 802.21 implementation and significant modifications to the UMTS model of the simulator were made. Several types of handovers were simulated and the obtained results were presented and discussed. Through the obtained results, it was possible to evaluate the performance of our framework during the different phases of the handover procedure, as well as the QoS metrics – packet delay, jitter and loss. Through the obtained results, it is possible to conclude that the IEEE 802.21 brings significant advantages regarding seamless mobility, if properly improved and applied to the specific technologies.

To finalize, it was discussed and presented a solution to achieve heterogeneous mobility in a real network scenario, composed by a commercial UMTS/HSPA network, WiMAX and Wi-Fi ANs, as well as an Android smartphone, taking advantage on the recent IEEE 802.21 developments. An experimental testbed was conceived and implemented to assess the handover process across multiple link-layer access technologies. The results have clearly showed that, under the proposed solution, the handover delay and packet loss are significantly lower than the ones resulting from the normal operation of a unmodified MIPv6 implementation (where the handover only occurs when the current connection is lost). Despite the noticeable improvements achieved, when the handover is triggered on MIPv6, some of the packets addressed to the previous active interface may still be dropped. To further improve the current mobility solution, a Fast MIPv6 approach can be used to assure handovers without packet loss.

7. Context-aware Media Independent Handovers

The increasing willingness to be connected in a full mobile environment is in the future an essential requirement for any user. The access can be made through several distinct wireless access technologies, e.g. Wi-Fi, WiMAX and 3GPP (UMTS, HSPA and/or LTE); they are not only distinct in terms of technology, but also in terms of applicability scenarios (local, metropolitan and wide area networks, respectively). The user and service demands allied to the mobile environment heterogeneity are increasing the need to achieve full mobility.

Although the MIH framework is able to improve the handover process, independently from the media, it defines an Information Server (IS) that only supports static network information about the access technologies. The handover preparation phase, which not only contains the process of Candidate Access Networks (CANs) discovery, but also the CANs resources availability check and the Target Access Network (TAN) resources allocation procedures, must be as short as possible to mitigate any traffic disruption during the handover process and, consequently, to provide a true make-before-break solution. Due to its complexity, the handover preparation phase, as described in section 6.3.2, is one of the most critical phases to control during the whole handover process. The IS is not able to provide real time and dynamic information from the Mobile Node (MN) or from the network to assist the vertical handover decision functions and procedures during the time-critical handover preparation phase [218].

Based on the abovementioned problem statement, the aim of this chapter is two-fold. First, it is described an optimization for the IEEE 802.21 framework, which allows the IS to store and manage context information. With a Context-aware IS (CIS), relevant static and dynamic information from the MNs and the network (such as the MN capabilities, user preferences, battery level, running applications, available network resources, system performance measurements, …) can be provided to the mobility management entities in runtime, and therefore optimize the vertical handover decision functions and procedures. A typical example that illustrates the limitations of the standard IS is the absence of real time dynamic information about the available network resources on the surrounding wireless access technologies of the MN. Without the available network resources information, the mobility management entity must query every possible CANs about its resources availability and thereafter decide on the chosen network during the time-critical handover preparation phase. This process is inefficient and takes considerable time depending on the number of available CANs. With the CIS optimization, one of the possible parameters to be managed has to do with the available network resources. Thus, the handover preparation phase procedures for discovering the CAN and its available resources can be performed in a single procedure, which will significantly reduce the overall time of the handover preparation phase. Secondly, it is presented the CIS Update Algorithm (CISUA), which decides when to trigger an update to the CIS, based on the access network resources availability variation. Finally, it is presented an evaluation of the proposed enhancements to the IEEE 802.21 framework. These mechanisms and procedures are implemented in the Network Simulator NS-2 (NS-2) tool, where specific add-ons have been introduced to establish the handover improvements between the different access technologies [219]. The final implementation supports the seamless interaction of these distinct technologies through IEEE 802.21 with the support of the CIS. The obtained results show that all the tested inter-technology handovers are indeed seamless, with handover execution delays in the order of 100 ms, and with a significant increase in the handover performance. Moreover, the achieved Quality of Service (QoS) metrics are also compliant with the services requirements, with low latency and jitter and no packet loss. It is concluded that fully and seamless mobility between distinct wireless access technologies and scenarios is achieved [220].

This chapter is organized as follows. Section 7.1 discusses the static MIH IS characteristics and limitations. Section 7.2 depicts the new concept of a CIS, including its main features and operation mode, whereas section 7.3 presents the CIS framework and how it can be integrated within the network. Finally, sectin 7.4 presents the required extensions that were built to the NS-2 simulator, as well as the simulation scenarios and the respective results obtained. Finally, section 7.6 provides a summary of the main topics discussed in this chapter.

7.1. Static Media Independent Handover Information Server

The Media Independent Information Service (MIIS) provides a framework by which a Media Independent Handover Function (MIHF), residing in the terminal or in the network side, discovers and obtains network information about the Access Networks (ANs) within a geographical area to facilitate network selection and handovers. The objective is to acquire a global view of all the heterogeneous networks relevant to the MN, facilitating seamless mobility procedures across these networks. The MIIS provides a generic mechanism to allow a service provider and/or a mobile user to exchange information about different CANs. The MIIS supports all types of ANs, such as IEEE 802 and 3GPP networks and allows that the collected information, which is stored and managed on the IS, is accessed from any single network. For example, by using an IEEE 802.11 AN the MN gets information not only about all the IEEE 802 based networks in its vicinity, but also from from 3GPP neighbouring networks. This capability allows the MN to use its currently active Serving Access Network (SAN) interface to query for information about the CANs nearby. Since the MN is not required to power up each one of its individual interfaces and establish network connectivity to retrieve information from the Radio Access Technologies (RATs), the MIIS procedures also reduce the terminal battery consumption significantly.

The MIIS provides very relevant information for optimizing the mobility decision entities on the appropriate CANs selection during the handover process. The type of information collected and managed by the MIIS is purely static, network related only, and stored on the IS. The static information provided by the MIIS through the IS is split into three main categories:

- General and Access Network Specific Information (GANSI): provides a general overview of different networks providing coverage within a specific area. For example, a list of available networks and their associated operators, roaming agreements between different operators, costs for using the network, operator charging policies, network security and QoS mechanisms;
- PoA Specific Information (PoASI): provides information about the different Points-of-Attachment (PoAs) for each one of the available ANs. For example, it includes the PoA addressing information, location, supported data rates, PHY and MAC types, as well as the channel parameters to optimize link layer connectivity;
- Other Network Specific Information (ONSI): AN, service or vendor/network specific information.

7.2. Context-aware Media Independent Handover Information Server

In this section the CIS rationale, features and operation mode are thoroughly described.

7.2.1. Context Information for Vertical Handover Decisions

The static network information provided by the MIIS is very important to optimize the vertical handover procedures. However, in the envisioned 4G environments, characterized by multi-access nodes and heterogeneous radio access technologies, multiple sources of information are required by the vertical handover decision algorithms to successfully control the handover procedure and select the most appropriated moment and target network for the handover, according (for example) to the user preferences, resources availability and device capabilities. The entity running the vertical handover algorithms in next generation wireless networks is the Network Mobility Manager (NMM), demanding real-time contextual information for the handover decisions, retrieved from both the network and the terminal side, which reflect the dynamic behaviour of the wireless heterogeneous environments. Therefore, a context-aware vertical handover strategy is fundamental to provide seamless handover procedures in heterogeneous environments.

With such a large scope of available contextual information for the vertical handover decision algorithms, it is important to categorize and classify this information. The contextual information classification can be based on its *location*, as well as its *changing frequency*. In what concerns the contextual information *location*, two major classification categories are identified on the top of the chain:

- ***Terminal Context Information***: contextual information driven from the MN, the user environment and the customer itself;
- ***Network Context Information***: contextual information collected and delivered by the context providers on the network side.

Additionally, besides the location-based information categories (Terminal and Network), context information should also be classified based on its *changing frequency*:

- ***Static Context Information***: information that does not change very often or at least during runtime;
- ***Real-Time Dynamic Context Information***: information that changes rapidly and must be updated constantly.

Based on the aforementioned contextual information categories, four different groups of contextual information for the vertical handover decision algorithms must be considered:

- ***Static Terminal Context Information (STCI)***: static information retrieved from the customer side;
    - *Device Capabilities*: the hardware resources provided by the MN, such as display size and resolution, memory, processor speed and available access interfaces, are required by the vertical handover algorithms to have a good knowledge of the MN and therefore hand it off to the most appropriated AN;
    - *Interface Preferences*: the user can have a list of pre-defined preferred ANs to connect during a handover procedure; this is important to allow the user to select among different wireless access technologies (e.g. between Wi-Fi and 3GPP ANs), as well as between the same access technology (e.g. between Wi-Fi Access Points – APs located on the same geographical area);
    - *Service Preferences*: expected received QoS and the precedence of service types are important metrics for the handover decision procedure;
    - *Cost*: cost is always a major consideration to users, as different networks may employ different charging models that may affect the user's choice of handoff.
- ***Dynamic Terminal Context Information (DTCI)***: real-time dynamic information retrieved from the customer side;
    - *Battery Level*: battery power is one of the most important resources from the mobile devices. Battery related information is an important asset for the vertical handover decision functions, enabling the later to manage the terminal handover to low power consumption access networks when the battery level decreases to a pre-defined threshold level;

- *Service/Application*: defines the required QoS parameters, such as bandwidth, delay and jitter, for the transparent delivery of the service; this will impact the selected access network for the vertical handover execution;
- *Available Access Networks*: given that various ANs can be under the MN coverage, it is important to have information about the ANs reachability at a specific time and place;
- *Velocity*: due to the overlaid architecture of heterogeneous wireless ANs, the velocity of the terminal is an important factor for the vertical handover algorithm. If the user is moving at high speeds, the most intelligent decision is to avoid handing off to an embedded wireless AN since a handoff back to the original wireless network will happen shortly.

- ***Static Network Context Information (SNCI)***: static information retrieved from the network side; this information is the only one that is already considered on the standardized IS.
- ***Dynamic Network Context Information (DNCI)***: real-time dynamic information retrieved from the network side;
    - *QoS Metrics*: a seamless handover procedure requires certain QoS metrics, such as available bandwidth, network latency and packet loss, from each CAN to be guaranteed;
    - *System Performance*: real time information about the radio access technology physical layer parameters, such as the channel propagation characteristics, interchannel interference, signal to noise ratio and bit-error-rate, are also important to assess the status of the CANs.

Figure 7-1 depicts the context information critical for the vertical handover decision functions, emphasizing the information groups (terminal and network) and categories (static and dynamic) described above.

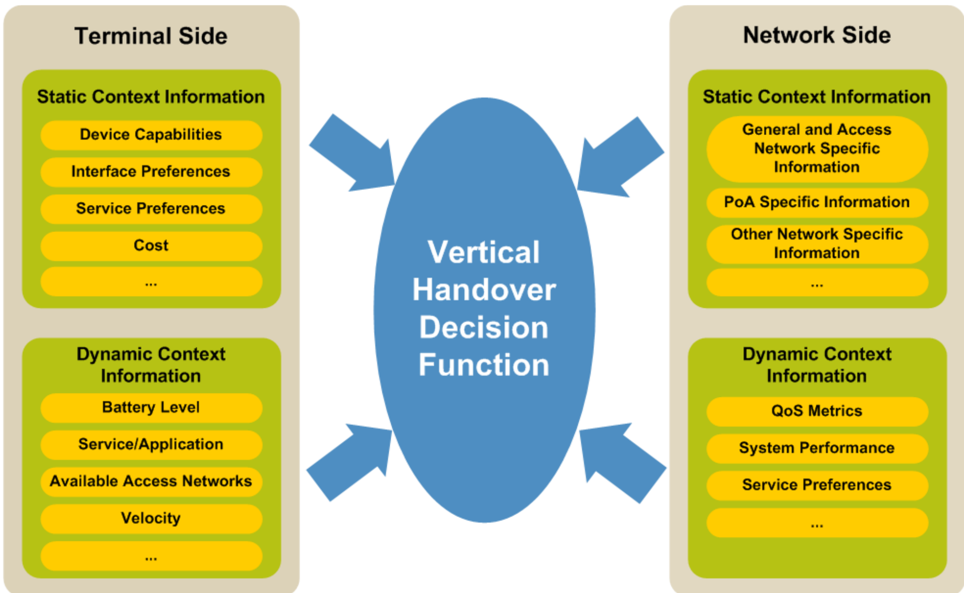

Figure 7-1: Context information for vertical handover decisions

7.2.2. Context-aware Information Server Functionalities

As described in section 7.1, the IS, which supports only static network-side information, is not able to accommodate all the demanding requirements raised by the vertical handover decision functions. It is very important to provide the mobility management entities with the aforementioned static and dynamic terminal and network side context information. To overcome this limitation and provide the NMM with critical real-time parameters for selecting the TAN to handoff the MN, we propose an evolution of the IS with the capability to store, process and manage real-time dynamic information obtained from both the network and the terminal side entities. The proposed enhanced version of the IS is referred as CIS.

Furthermore, the CIS is also responsible to store the vertical handover policy rules. By definition, a policy based management system operation is determined by a set of rules and instructions. The policy rules are responsible for defining the behaviour of the system and are triggered upon the arrival of an event, either from the network or from the terminal side. Shortly, the CIS is composed by two core functionalities:

- ***Context Information***: stores and manages static and real-time varying information retrieved from both the terminal and the network side;
- ***Vertical Handover Policies***: stores and manages terminal and network vertical handover policies that will be applied by the vertical handover decision functions on the NMM.

Figure 7-2 illustrates the high level structure of the CIS. The core functionalities that compose the CIS, namely the Context Information Repository (CIR) and the Vertical Handover Policies Repository (VHOPR), are depicted in the center of the figure. The CIR is split in two main information groups based on the information location – Terminal and Network Information Groups. Within each location information group, two information categories are identified based on the information variation frequency – static and dynamic. The four resulting contextual information categories of the CIR are the SNCI, DNCI, STCI and DTCI.

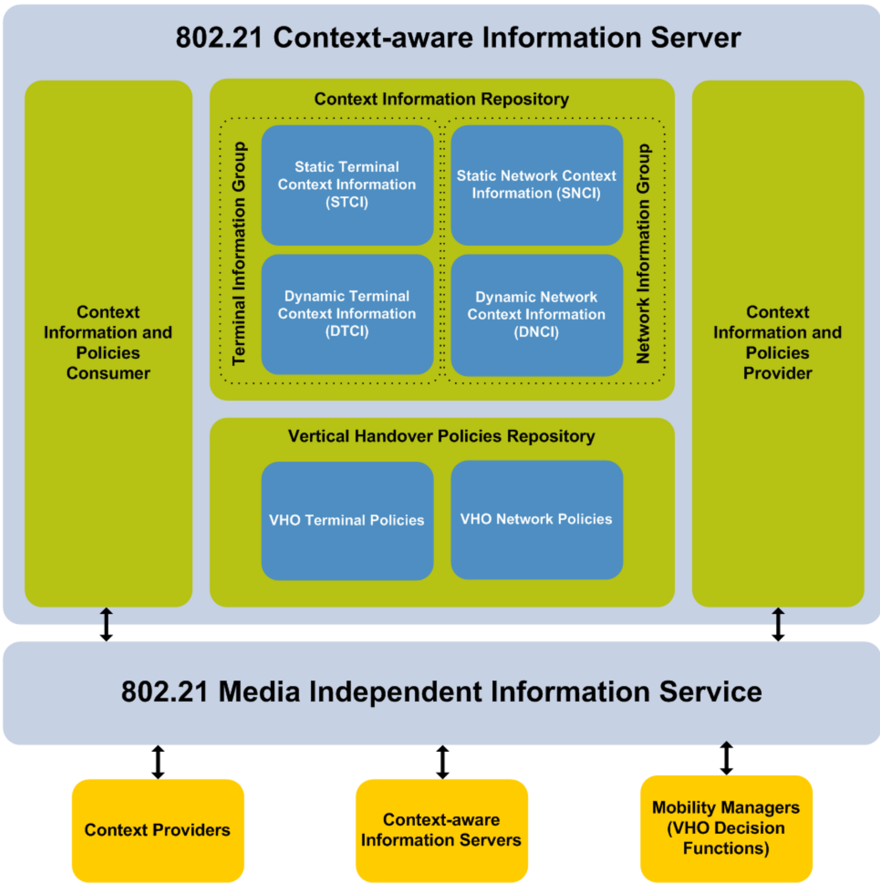

Figure 7-2: MIH CIS structure

As for the CIR module, the VHOPR is also split in two internal policy groups. One of the groups contains vertical handover policies related with the MN side, whereas the other one is responsible for storing the network side policies to be applied during the handover procedures. The vertical handover policies are periodically retrieved by the policy engine running on the vertical handover decision functions, either on the terminal or on the network side. Moreover, the policy engine also queries the CIS, in particular the CIR, to retrieve the required context information to apply the vertical handover policy rules. Additionally, besides the CIR and VHOPR core functionalities, the CIS also provides the Context Information and Policies Consumer (CIPC) module, shown on the left-side of Figure 7-2, which is responsible for processing the context information retrieved from the Context Information Providers (CIPs) and from the neighbor CIS. On the right side of Figure 7-2, it is illustrated the Context Information and Policies Provider (CIPP) module, which is responsible for delivering the required context information and policies to the neighbor CIS, as well as to the vertical handover decision functions installed on the NMM. Both the CIPC and CIPP use the messages and primitives provided by the IEEE 802.21 framework, in particular by the MIIS.

7.3. Distributed Context-aware Media Independent Handover Framework

Following the CIS description from the previous section, we will now describe a heterogeneous mobile architecture enhanced with contextual information. An extension to the IEEE 802.21 standard is also proposed to transport the context information between the several context entities within the architecture. Finally, an algorithm is proposed to define the update frequency of the contextual information towards the mobility decision entities.

7.3.1. Context-aware Information Server Framework Description

In a centralized network deployment, the CIS is located at a centralized entity of the operator network. With this topology, the CIS needs to be very powerful, with large memory and Central Processing Unit (CPU) capacity to serve a considerable number of Access Network Gateways (AN-GWs), PoAs and MN, while offering redundancy. Since the core is located anywhere from dozens to hundreds of kilometers from the AN-GWs, BSs and MNs, the communication with the CIS in a centralized approach requires long-distance backhauling. Instead of following a centralized approach for the CIS implementation, we propose a distributed network deployment, downsizing the CPU and memory capacity requirements, as well as reducing the amount of long-distance backhauling to the core. Summarizing, the following main advantages are obtained with the CIS distributed-approach:

- ***Redundancy***: elimination of a single point of failure: when a CIS fails, it impacts only a small segment of the overall network;
- ***Reduced latency***: latency is lowered, increasing the probability for successful vertical handover.

We propose the CIS distributed between the Core Network (CN) and ANs, as well as on the MNs (Figure 7-3). Its main functionalities are as follows:

- ***Terminal Context-aware Information Server (TCIS)***: contains relevant static and dynamic information from the terminal side – STCI and DTCI categories described in section 7.2.1. The TCIS is installed on the MN and its main role is to assist the mobility management procedures triggered and controlled by the MN, as well as network initiated mobility procedures that require MN assistance;
- ***Access network Context-aware Information Server (ACIS)***: handles dynamic contextual information – DNCI category depicted in section 7.2.1. The main objective of the ACIS is to optimize the Network Initiated Handover (NIHO) procedures, as well as assisting on handover procedures triggered and controlled by the MN. Since the dynamic context information retrieved from the AN is highly variable, in order to reduce latency and provide redundancy each AN contains its own ACIS;
- ***Core network Context-aware Information Server (CCIS)***: includes static, network side, contextual information – SNCI described in section 7.2.1. The CCIS is distributed through the operator higher-level segment of the network, the CN, and its main goal is to assist both, network and mobile, as well as triggered or controlled handover procedures.

Figure 7-3 illustrates an IEEE 802.21 MIH compliant context-aware mobility architecture, composed by the Radio Access Network (RAN), the AN and the CN. The RAN is composed by the network PoA, which provides wireless connectivity to the end users, whereas the AN contains the AN-GWs, responsible for providing connectivity to the CN. Any type of RAN, such as 3GPP UMTS/HSPA/LTE, WiMAX or Wi-Fi, can be utilized and supported by the framework. Finally, the CN contains the DHCP, DNS and AAA servers.

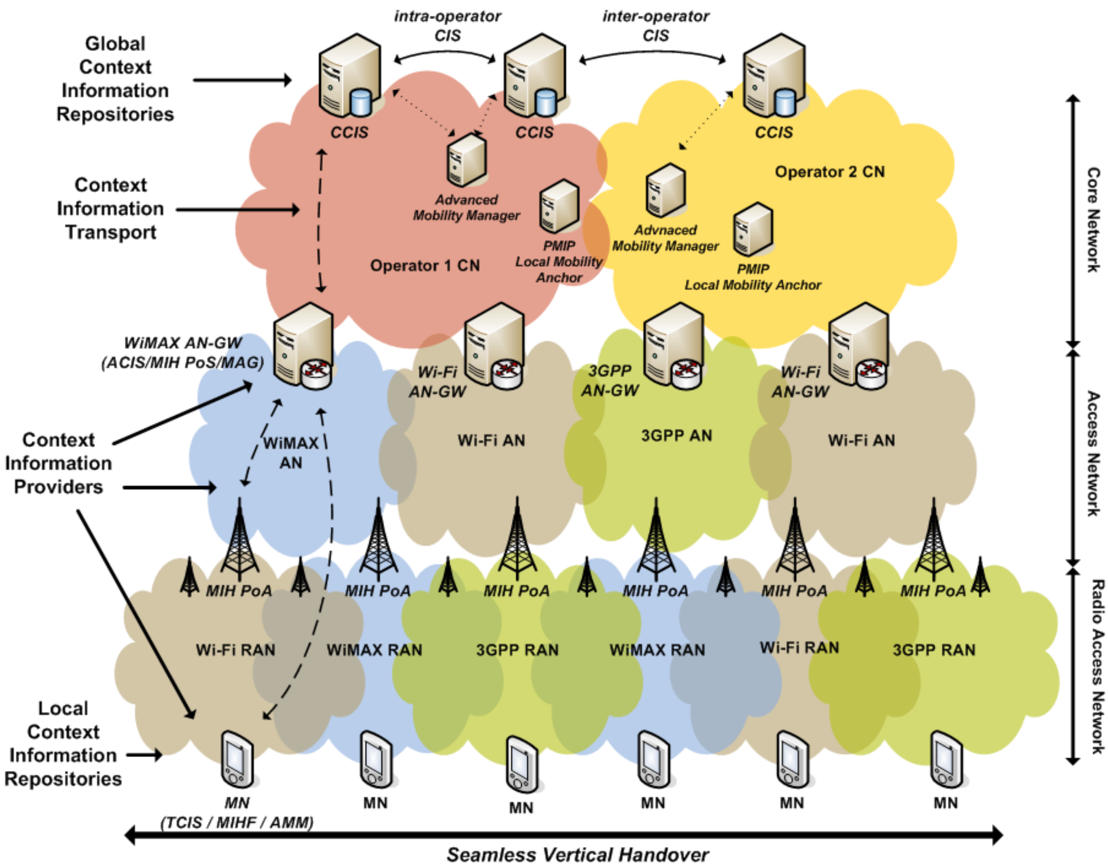

Figure 7-3: Context-aware MIH mobility architecture

The 802.21 MIH entities are also depicted in Figure 7-3. A client-side instance of the MIHF is included on the MN and establishes communication with the MIHF instance running on the network side PoS. The PoS can either be located on the PoA or on the AN-GWs. Finally, the proposed framework of distributed CIS is illustrated, including the TCIS on the MN, the ACIS on the AN-GW and the CCIS on the core. Furthermore, the context information entities that interface with the CIS are presented as well. The CIPs, located on the MN, PoAs and AN-GWs, provide the context information to the CIS, which stores it in the CIRs.

To manage the context information within the IEEE 802.21 framework, an extended version of the MIH protocol is proposed to support context information transfer. For example, IEEE 802.21 is used to transport context information between the CIPs and the CISs, as well as to distribute the collected information with the different instances of the CIS. Towards this goal, a new mechanism called *Media Independent Handover Context Information* (*MIH_Context_Information*), part of the IEEE 802.21 MIIS, is defined to transport the context information within the MIH platform.

Figure 7-4 illustrates the distributed CIS, in which the context information is provided by the AN-GWs using the *MIH_Context_Information* mechanism. As illustrated, the AN-GWs (1…N) are anchor entities, collecting and aggregating real-time information from the ANs. The CISs are distributed on the operator network, and retrieve real-time context information directly from the AN-GWs using the IEEE 802.21 *MIH_Context_Information* mechanism.

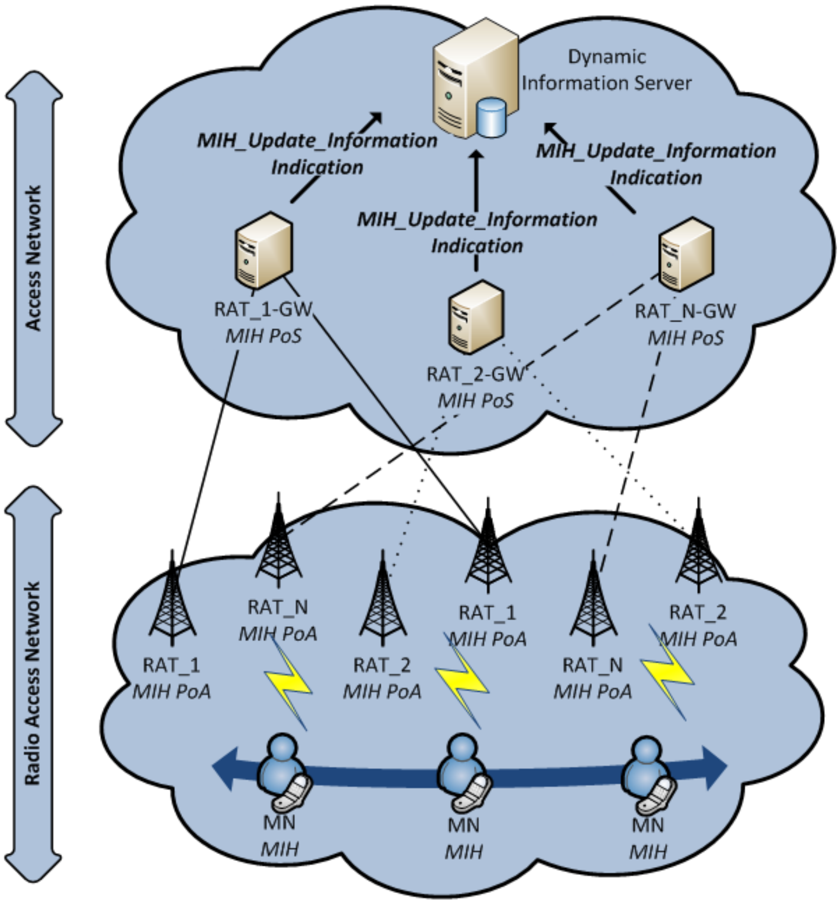

Figure 7-4: CIS communication architecture

7.3.2. Context-aware Information Server Update Algorithm

Herein, to illustrate the advantage of the CIS over the traditional IS, we will select and focus on only one of the contextual information types abovementioned, in particular the available resources on the radio access technologies.

By supporting a CIS, the MIIS will be able to simultaneously deliver the CANs surrounding the MN area, as well as the available radio resources for each one of them (using the IEEE 802.21 *MIH_Get_Information* mechanism). This will enable the decision algorithm to immediately select the TAN, without having to individually query all the available CANs after their discovery. This, in turn, will reduce the required time for the handover preparation phase, since it will convey on the same message the surrounding ANs of the MN and the resources available on each one of them.

Since the radio links resources are very variable, producing many changes in short periods of time, it is necessary to define an algorithm, which decides when the CIS should be updated with new information provided by the access technologies PoAs. The CIS Update Algorithm (CISUA) prevents the network flooding with signaling messages from the PoAs and is based on the following parameters:

- ***Resources Occupancy Control Point (ROCP)***: maximum acceptable value for the wireless link occupancy – when this value is reached, the resources occupancy on the wireless link is critical and therefore the update frequency of the CIS will increase;
- ***Resources Occupancy (RO)***: occupied resources on the wireless link;
- ***Resources Occupancy Variation (ΔRO)***: variation of occupied resources on the wireless link;
- ***Resources Threshold Interval (RTI)***: threshold interval on the post-ROCP phase;
- ***N***: Number of threshold intervals on the post-ROCP phase;

- ***Flexible Resources Occupancy Variation (ΔFRO)***: resources occupancy variation tolerance on the pre-ROCP phase;
- ***Critical Resources Occupancy Variation (ΔCRO)***: resources occupancy variation tolerance on the post-ROCP phase.

Algorithm 1: Context-aware Information Server Update Algorithm (CISUA)

$ROCP$: Resources Occupancy Control Point
RO: Resources Occupancy
$\triangle_{RO}$: Resources Occupancy Variation
RTI: Resources Threshold Interval
$\triangle_{FRO}$: Flexible Resources Occupancy Variation
N: Number of Critical Variation Intervals
$\triangle_{CRO[N]}$: Critical Resources Occupancy Variation

```
/* Resources variation detected on the RAN-GW */
if RO > ROCP then                              /* ROCP surpassed? */
    for i ← 1 to N do
        if RO < (ROCP + RTI × i) then
            if △RO > △CRO[i] then
                send MIH_Context_Information to CIS;
            break;
else                                           /* ROCP not reached? */
    if △RO > △FRO then
        send MIH_Context_Information to CIS;
/* Periodic (configured) update timer reached */
if RO < ROCP then
    send MIH_Context_Information to CIS;
```

The CISUA is split in two main phases: pre-ROCP and post-ROCP. During the pre-ROCP phase, the RO on the wireless link is low, and therefore it is not necessary to update the CIS very frequently. Only very high variations of the RO, i.e. higher than ΔFRO, trigger a *MIH_Context_Information Indication* message to the CIS by the PoAs. During the pre-ROCP phase, update messages are also sent when a pre-defined periodic timer is reached. On the post-ROCP phase of the algorithm, the CIS update frequency is not periodic and depends on a set of combined factors (RO, ΔRO, RTI & ΔCRO) of the wireless link. When the RO increases, the ΔCRO tolerance decreases and therefore the *MIH_Context_Information Indication* messages frequency sent to the CIS is higher (Algorithm 1).

Table 7-1 provides an example of the CISUA operation with the ROCP equal to 75 %. Between 75 % and 100 %, 5 % of RTI are defined to handle the resources variations. Each RTI has a specific tolerance to the resources variation in the AN (*ΔCRO*): the closer the *RTI* interval approaches the maximum *RO* (100 %), the lower the tolerance to resources variations gets (*ΔCRO*).

RTI (%)	Δ CRO (%)				
	< 0.5 %	[0.5 %, 1 %]	[1 %, 1.5 %]	[1.5 %, 2 %]	> 2 %
75 – 80 %	X	X	X	X	Update
80 – 85 %	X	X	**X**	Update	Update
85 – 90 %	X	X	Update	Update	Update
90 – 95 %	X	**Update**	Update	Update	Update
95 – 100 %	Update	Update	Update	Update	Update

Table 7-1: CISUA usage example

For example, based on Table 7-1, assuming that the RTI is between [80 % – 85 %] and the ΔCRO is within [1 % - 1.5 %], no *MIH_Context_Information* message will be sent by the access technology to the CIS. In this case, although the ROCP (75 %) is surpassed, since the RO is still relatively far from the maximum occupancy level (RO = 100 %), the algorithm is tolerant to ΔRO below 1 %. Another example, also based on Table 7-1, is the following: assuming the [90 % - 95 %] RO interval, but with a ΔRO within [0.5 % – 1 %], the *MIH_Context_Information* message is triggered by the PoA towards the CIS. In this example, the RO is higher and therefore the tolerance to the ΔRO decreases. According to the output of the CISUA, the PoAs detect the resources variations and trigger, if necessary, an update message towards the CIS. In detail, as illustrated in Figure 7-5, the several wireless access technologies PoAs send the *MIH_Context_Information Indication* message directly to the CIS. Consequently, the CIS updates its database with the new resources information.

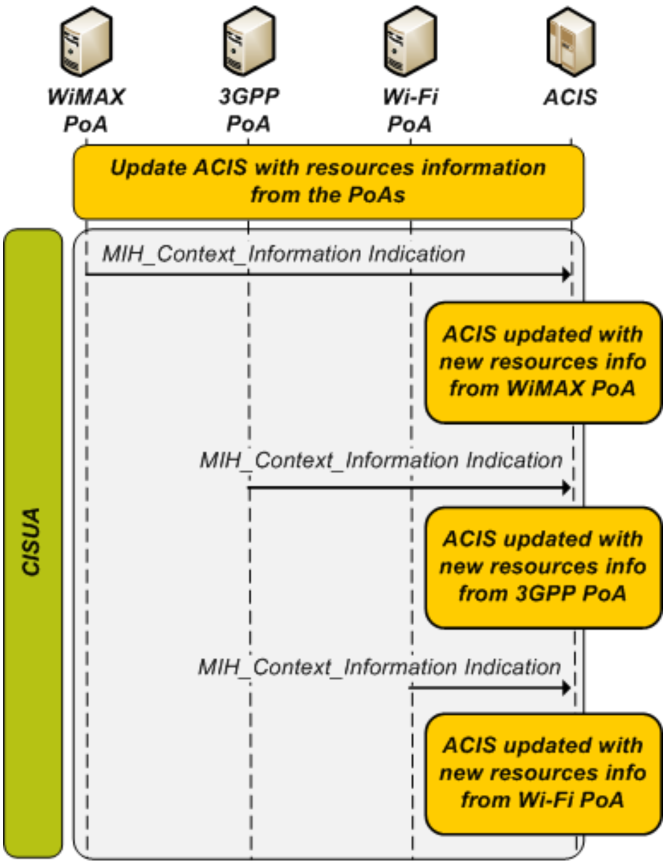

Figure 7-5: *MIH_Context_Information* mechanism

7.3.3. Seamless Handover Procedures with Context-aware Information Server

This section provides a description of a MIH procedure optimized with the CIS. Once the MN decides to handover to a new network, either due to loss of signal quality or due to user preferences, the MN triggers the *MIH_Get_Information Request* mechanism to retrieve, simultaneously, information about the CANs surrounding the MN, as well as the available resources on each one of them. This new sub-phase is part of the handover preparation phase and merges the *CANs Discovery* and the *CANs Resources Availability Check* procedures, creating a new sub-phase designated *CANs Discovery and Resources Availability Check*. With the proposed modifications, the CIS contains real-time updated information about the available radio resources in each one of the underlying ANs. The CIS provides this information to the MN using the *MIH_Get_Information Response* message. Therefore, the objective of the *MIH_Get_Information* mechanism is extended when compared with the original one, providing information about the available CANs for the handover, as well as the amount of resources available on each one of them.

Figure 7-6 illustrates the handover preparation phase with the CIS, including both the *CANs Discovery & Resources Availability Check* procedure and the *TAN Resources Commit* procedure. After receiving and processing the *MIH_Get_Information Response* message, the MN immediately selects the TAN based on the networks availability (location and resources) retrieved from the CIS. Since the CIS provides the available CANs and the correspondent available resources on each one of them, the handover decision is taken without requiring any further actions. Therefore, the MN does not have to go through the *MIH_MN_HO_Candidate_Query* and *MIH_N2N_HO_Query_Resources* mechanisms to query each one of the CANs about their resources, as described in section 6.3.2.2, significantly optimizing the handover preparation phase. Furthermore, using this procedure, the MN power management is optimized because only the selected radio interface for the handover is activated, leaving the remaining ones in standby mode.

After obtaining the topology and resources information through the CIS, the MN is able to trigger the resources activation in the TAN using the *MIH_MN_HO_Commit* and *MIH_N2N_HO_Commit* procedures (see section 6.3.2.4). As soon as the resources activation process is finished, the MN switches to the TAN and terminates the handover process by eliminating the resources that were allocated in the SAN.

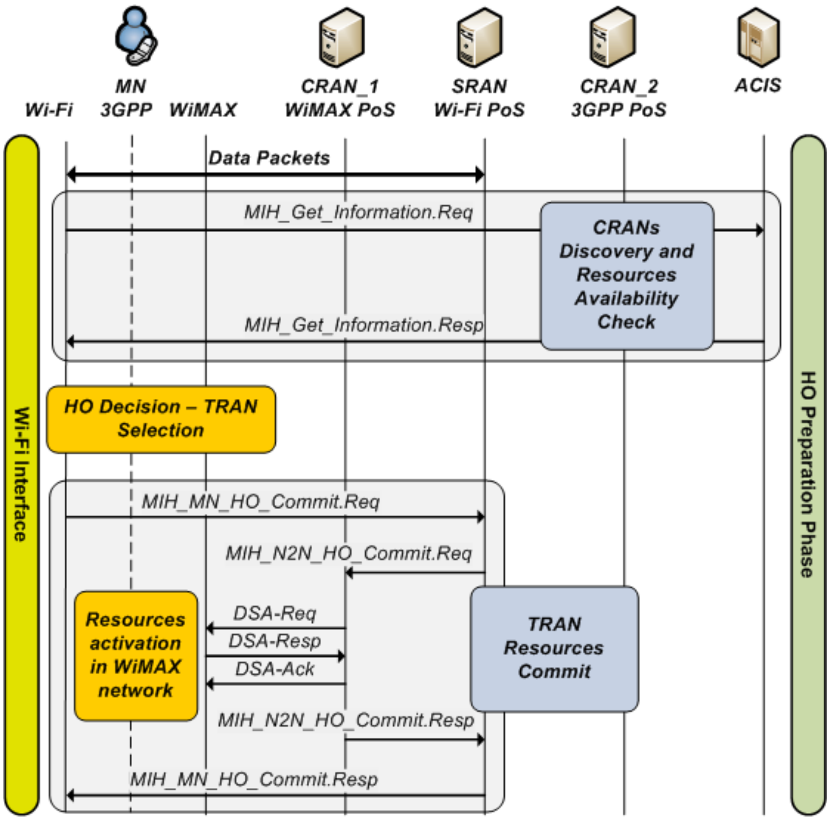

Figure 7-6: Handover preparation phase with CIS

7.4. CIS MIH Protocol Extensions

The defined *MIH_Context_Information* mechanism is composed by the *MIH_Context_Information.indication* primitive and by the *MIH_Context_Information Indication* message. The *MIH_Context_Information.indication* primitive is exchanged between the MIHU and the MIHF through the MIH_SAP interface. If the primitive is sent to a remote MIHF, the local MIHF triggers the *MIH_Context_Information Indication* message, which is sent between the peer MIHFs using the MIH_NET_SAP interface.

Table 7-2 describes the *MIH_Context_Information.indication* primitive.

Only one of the following parameters can be included in the *MIH_Context_Information* message:

- InfoUpdateBinaryDataList;
- InfoUpdateRDFDataList;
- InfoUpdateRDFSchemaURL;
- InfoUpdateRDFSchemaList.

The *MIH_Context_Information Indication* message parameters are similar to the ones presented on Table 7-2. The only difference is the additional parameter *SourceIdentifier*, which identifies the MIHF that sent the message to the peer MIHF.

Table 7-2: *MIH_Context_Information.indication* primitive parameters

802.21 Primitive	Parameter Name	Description
MIH_Context_Information.indication	*DestinationIdentifier*	MIHF that will be the destination of this message
	InfoUpdateBinary DataList	(Optional) A list of TLV updates. The order of the updates in the list identifies the priority of the update. The first update has the highest priority to be processed by MIIS
	InfoUpdateRDF DataList	(Optional) A list of RDF updates. The order of the updates in the list identifies the priority of the update. The first update has the highest priority to be processed by MIIS
	InfoUpdateRDF SchemaURLList	(Optional) A RDF schema URL update. This field is required only when the value is "TRUE", which indicates to update a list of RDF schema URLs
	InfoUpdateRDF SchemaList	(Optional) A list of RDF schema updates. The order of the updates in the list identifies the priority to be processed by MIIS
	UpdateNetworkType	The type of the network being used by the updater

7.5. Simulation Performance Evaluation

This section is dedicated to the evaluation tests. Shortly, it is provided an evaluation of the time required to support the signalling procedures defined by IEEE 802.21 CIS.

The simulations were made in the NS-2 simulator using the NIST add-on. The following modifications were made to the NIST module:

- Implementation of the *MIH_Context_Information.indication* primitive on the MIH_SAP (as described in section 7.4);
- Implementation of the *MIH_Context_Information Indication* primitive on the MIH_NET_SAP (as described in section 7.4);
- Adaptation of the standardized static IS to support dynamic information (CIS) from the RATs.

7.5.1. Context-aware Vertical Handover Signaling Measurements

7.5.1.1. Simulated Scenario and Tests Methodology

The scenario illustrated in Figure 6-18 was used to evaluate the performance of a seamless handover procedure with the CIS. The testing conditions are identical to the ones described in section 6.5. Shortly, the radio access technologies involved in the experimental scenario are Wi-Fi, WiMAX and UMTS. IEEE 802.21 entities are located on the MN, on the AN-GWs and on the CIS. Three inter-technology handover scenarios are considered: 1) Wi-Fi to WiMAX, 2) WiMAX to UMTS and 3) UMTS to Wi-Fi, providing a case study for all the possible combinations between these ANs. To load the wireless environment, the simulation scenario integrates several background users, distributed across all the radio access technologies, each one consuming 512 Kbps. According to the handover scenario considered, the MN receives a VoIP call with 128 Kbps and/or an IPTV stream with 2 Mbps. The presented simulation values represent the average of twenty independent runs in the NS-2 simulator.

With the CIS, all the handover phases remain as specified in section 6.3, except for the handover preparation phase. As detailed, the preparation phase of the handover with the IS has three procedures: 1) *CANs Discovery*, 2) *CANs Resources Availability Check* and 3) *TAN Resources Commit*. With the CIS, as detailed in section 7.3, the handover preparation phase is shortened to two procedures: 1) *CANs Discovery & Resources Availability Check* and 2) *TAN Resources Commit*. With the CIS approach, the *CANs Discovery* phase, in which the candidate access networks are queried about their resources availability, is no longer needed. Therefore, the handover preparation phase is the one that is optimized due to the context information supported by the IS. To enable a thorough comparison between the IEEE 802.21 IS and CIS performance, we will focus our evaluation on the handover preparation phase, although the handover execution and completion phases are also very important.

7.5.1.2. Results

Hereafter it is presented the results obtained along this study. The preparation, execution and completion phases of the handover are evaluated in this section, as well as the overall handover process. With special attention to the preparation phase, its internal procedures are thoroughly analyzed – *CANs Discovery*, *CANs Resources Availability Check* and *TAN Resources Commit*.

7.5.1.2.1 Handover Preparation Phase

Herein the measured values for the preparation phase of each one of the inter-technology handovers are described.

Wi-Fi to WiMAX Handover

Figure 7-7 illustrates the preparation phase for the Wi-Fi to WiMAX handover in two distinct situations: one with the standard IS and another with the CIS. The internal procedures of the handover preparation are included for the IS and the CIS scenarios.

As illustrated in the previous figure, the handover preparation phase with the standardized IS takes approximately 125 ms until the number of simultaneous background users is increased up to 6, which is the threshold limit for the Wi-Fi link saturation. The preparation time is distributed in three internal procedures: 35 ms for *CANs Discovery*, 40 ms for *CANs Resources Availability Check* and 50 ms for *TAN Resources Commit*. These values are easily explained due to the one-way delay of the Wi-Fi and the wired links. The one-way delay of the wired part of the network is approximately 5 – 10 ms for the three-handover cases presented in this paper, whereas the one-way delay on the wireless link depends on the access technology. For the Wi-Fi link, the one-way delay is approximately 10 – 12 ms. The time interval spent on each internal procedure of this phase can be explained if we sum up all the one-way delays in the wireless and wired links. For example, the 35 ms spent by *CANs Discovery* procedure are due to the *MIH_Get_Information.req* message sent from the MN to the IS (uplink Wi-Fi wireless hop and wired hop) and the *MIH_Get_Information.rsp* message sent from the IS to the MN (downlink wired hop and Wi-Fi hop). Summing the one-way delays associated with the wired and the wireless links (uplink and downlink) we obtain approximately 35 ms. The values measured for the *CANs Resources Availability Check* and the *TAN Resources Commit* procedures have a similar justification.

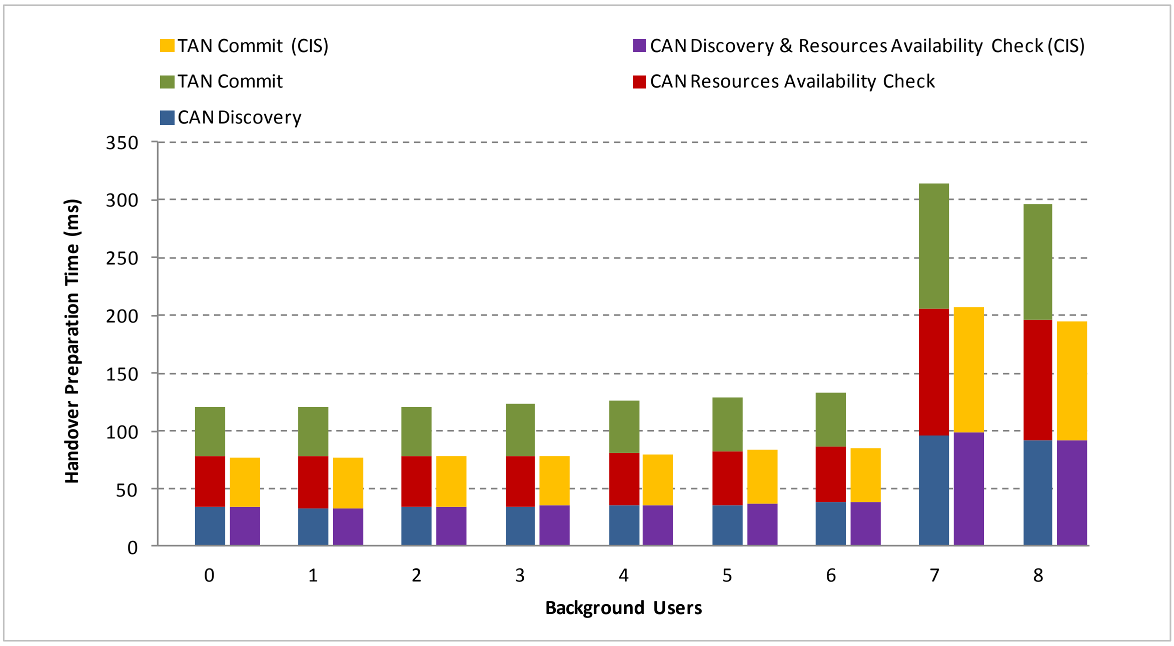

Figure 7-7: Wi-Fi to WiMAX handover preparation phase

With respect to the preparation phase with the CIS, the time spent is approximately 80 ms. The preparation phase starts with the *CANs Discovery and Resources Availabillity Check* procedure, which takes approximately 35 ms. Regarding the *TAN Resources Commit* procedure, it is approximately 45 ms. These values are easily explained due to the one-way delay of the Wi-Fi and wired links.

When the number of background users goes beyond 6, the wireless link saturates and the measured values start increasing significantly. For example, for 7 simultaneous background users, the total background traffic is approximately 3.6 Mbps (each background user injects 512 Kbps). Since the IPTV stream is 2 Mbps, the total data rate in the wireless channel is 5.6 Mbps, already surpassing the limit for the downlink channel of the Wi-Fi access technology (5.5 Mbps).

WiMAX to UMTS Handover

In this section, the behavior of the IS and CIS solution is analyzed for the WiMAX to UMTS handover. Analyzing Figure 7-8, we can conclude that the total handover preparation time (36 ms) is approximately constant, independently of the number of background users. Since this is a typical NIHO scenario, the HO preparation phase procedures are simpler because the MN does not have to intervene. Therefore, there is no communication with the MN, and consequently, the procedures of the preparation phase are less time-consuming (*CANs Discovery* – 12 ms; *CANs Resources Availability Check* – 13 ms; *TAN Resources Commit* – 11 ms) when compared with the ones from the Wi-Fi to WiMAX handover, in which the handover preparation time is around 125 ms. Since the wireless link does not intervene in the handover preparation phase, these values can be explained by the one-way delay given by the wired part of the network (one-way delay is approximately 5 – 10 ms). The increase in the background users does not affect the handover preparation phase because this is a NIHO scenario, and therefore, the wireless link is not involved in this phase.

For the CIS approach, we verify that the handover preparation time is approximately constant, 23 ms, independently of the background users' number. In a NIHO scenario, as in this situation, the preparation phase is simpler because the MN does not have to intervene in the preparation procedures. Therefore there is no communication with the MN and consequently the internal procedures of the handover preparation phase are less time-consuming (*CANs Discovery and Resources Availability Check* – 12 ms*, TAN Resources Commit* – 11 ms) when compared with the ones from the Wi-Fi to WiMAX case.

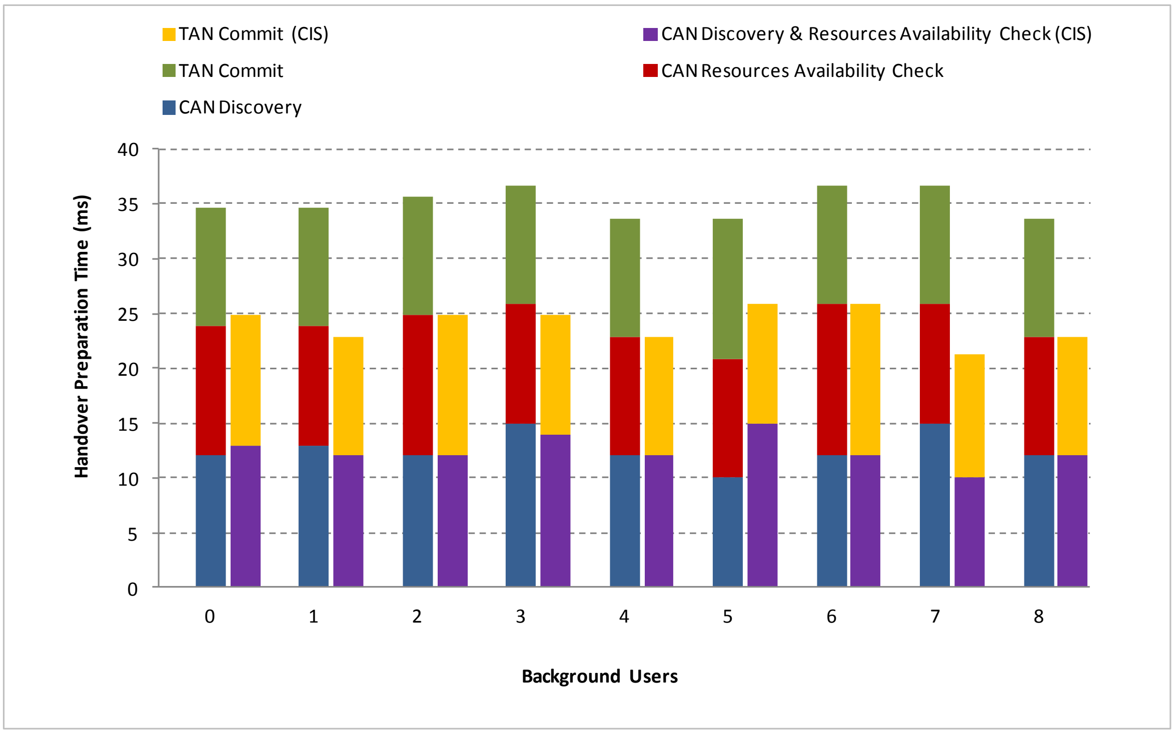

Figure 7-8: WiMAX to UMTS handover preparation phase

UMTS to Wi-Fi Handover

From Figure 7-9, we can see that the handover preparation time with the IS approach is around 31 ms, independently of the background users' number.

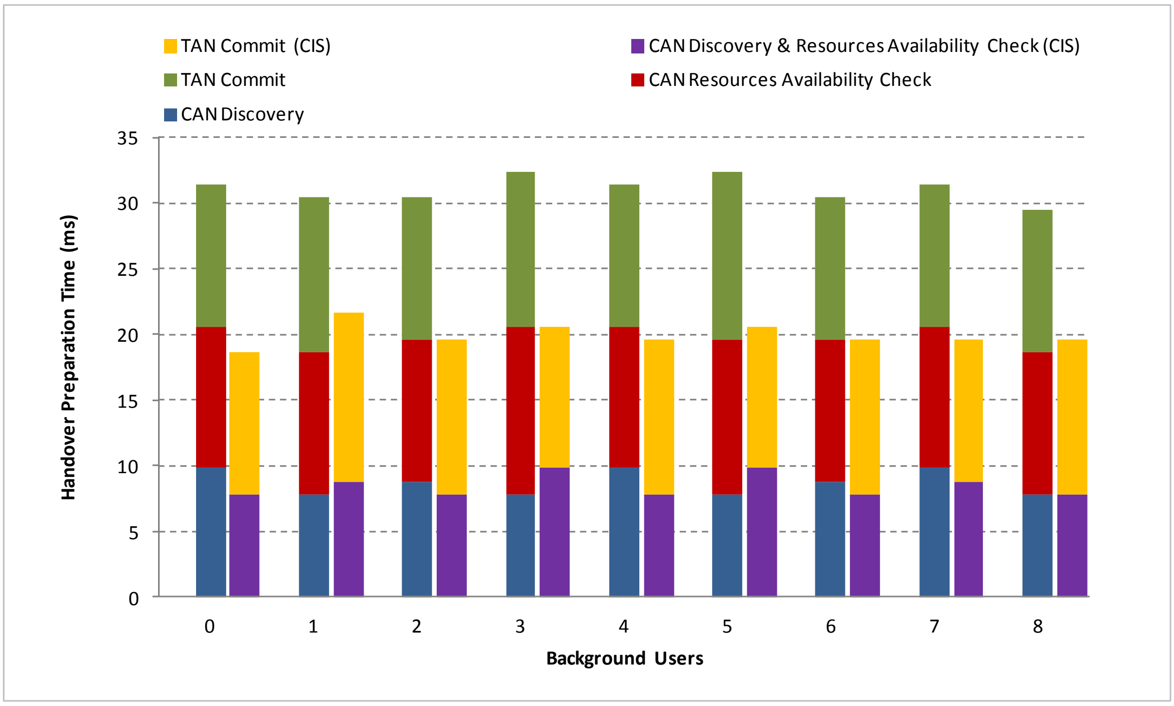

Figure 7-9: UMTS to Wi-Fi handover preparation phase

As in the WiMAX to UMTS handover scenario, illustrated in Figure 7-8, this value is significantly smaller than the 125 ms obtained for the handover preparation phase of the MIHO from Wi-Fi to WiMAX (Figure 7-7). The reason for this behavior is related with the fact that, in a NIHO scenario, the UMTS wireless link is not involved in the handover preparation phase, and therefore the internal procedures will not be affected by the UMTS one-way delay (approximately 40 ms).

In what the CIS approach is concerned, the preparation phase of the handover takes approximately 19 ms (*CANs Discovery and Resources Availability Check* – 8 ms, *TAN Resources Commit* – 11 ms), independently of the background users' number.

7.5.1.2.2 Handover Execution and Completion Phases

The execution phase for the three handover scenarios is illustrated in Figure 7-10. In the handover from Wi-Fi to WiMAX, the execution time is approximately constant (45 ms) when the number of background users increases. For the WiMAX to UMTS handover scenario, the time interval is approximately 110 ms and constant. This time is spent on the link level association with the UMTS network and on the acquisition of a new IP address. Therefore, the performance of the handover execution phase heavily depends on the type of TAN to which the user is handing off. Since the UMTS network consumes a significant amount of time on the link layer association, the handover execution time for this scenario (110 ms) is very high compared with the one obtained for the Wi-Fi to WiMAX handover (45 ms). Nevertheless, it is still able to seamlessly handover the MN services to the UMTS AN. Finally, the execution time for the UMTS to Wi-Fi handover is approximately 48 ms. Since the CIS enhancements have no impact on the handover execution phase, the values here presented are equal for both the IS and the CIS approaches. Finally we depict the handover completion phase in Figure 7-11. In the Wi-Fi to WiMAX scenario, the measured values increase from approximately 70 ms to 125 ms, whereas in the WiMAX to UMTS and UMTS to Wi-Fi handovers the obtained values are approximately constant, 115 ms and 35 ms, respectively.

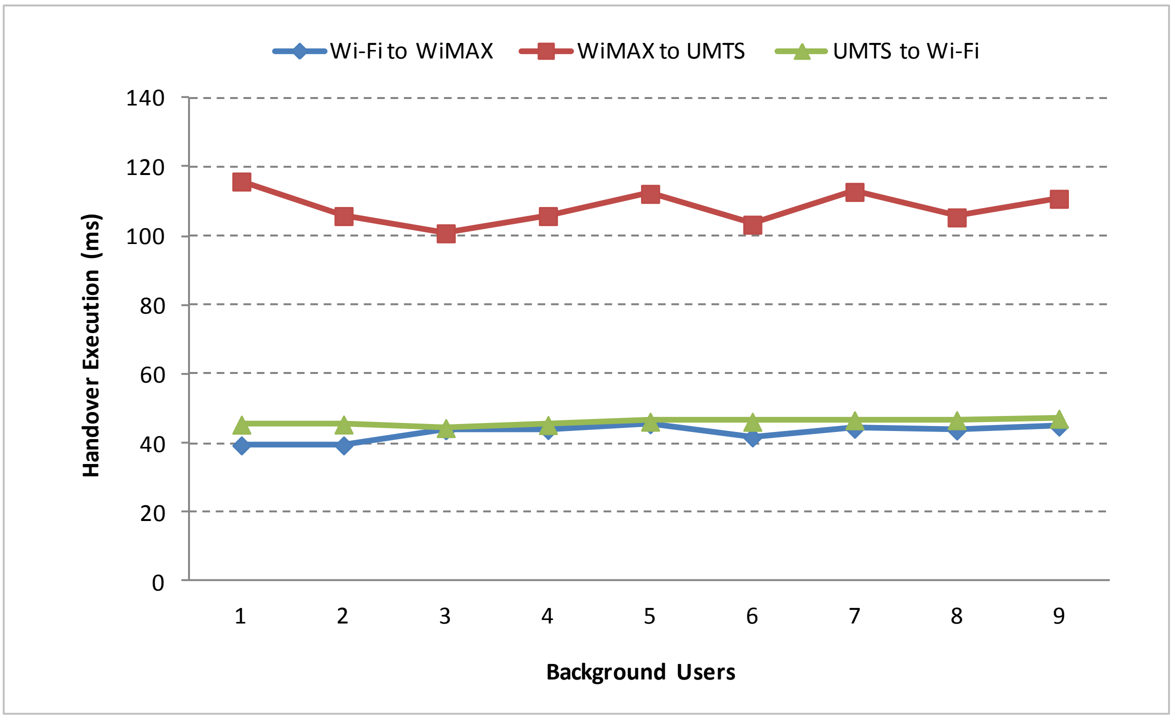

Figure 7-10: Handover Execution Phases

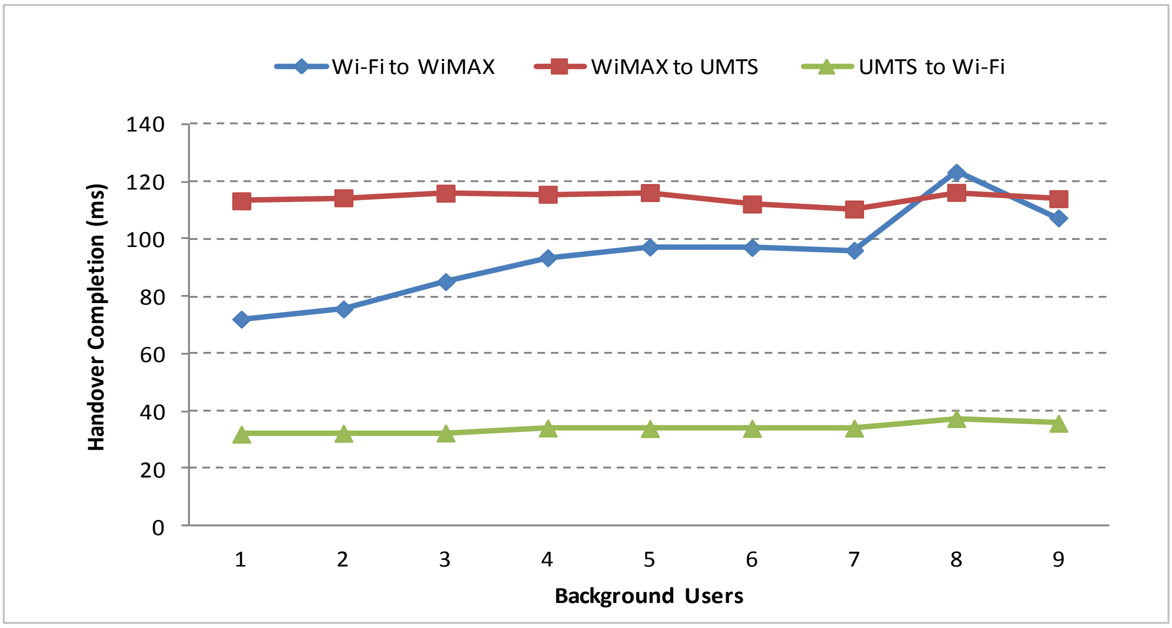

Figure 7-11: Handover Completion Phases

7.5.1.2.3 IS vs CIS Comparison

Figure 7-12 illustrates the overall time of the handover process for all the use-cases studied using the standard IS and the CIS. By observing this graph we can once more highlight the enhancement brought by the capability of the IS to support context information. The evidence of the enhancement is clearer in the Wi-Fi to WiMAX scenario. This happens because the handover in this case is MIHO, using more the wireless access technologies (wireless links have a considerable high delay) during the process (more specifically in the preparation phase) which leads to a higher overall time; on the other hand the CIS enhances the preparation phase by making it shorter (reducing the number of messages that use the wireless links).

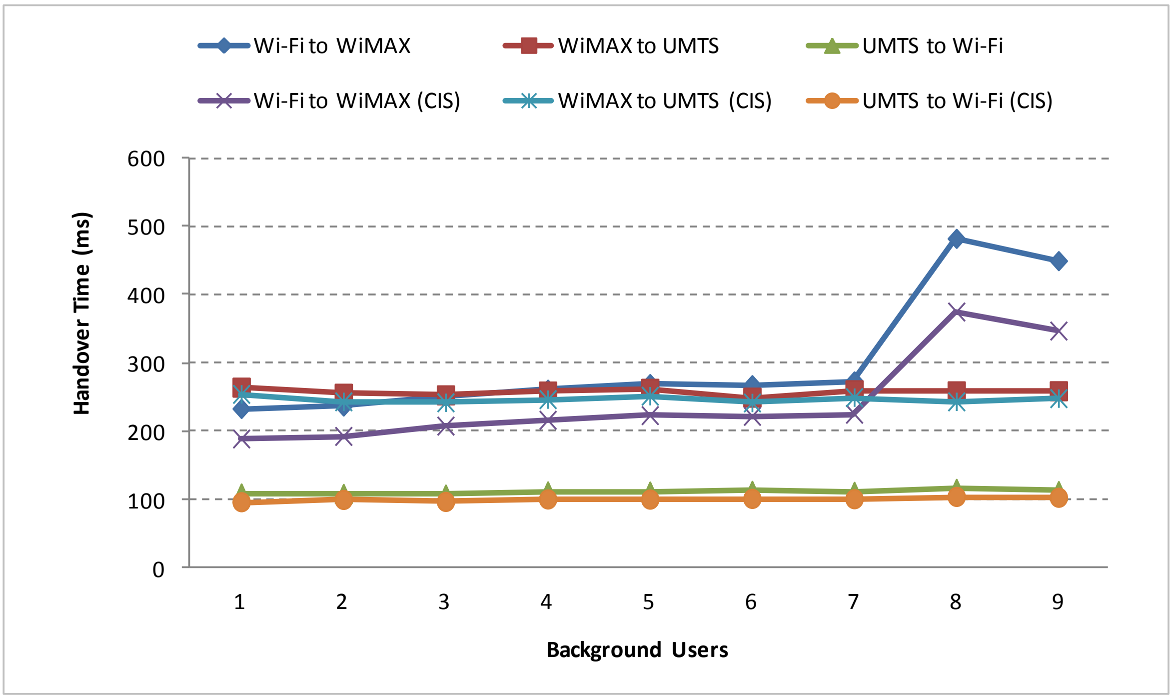

Figure 7-12: IS vs CIS handover procedure

7.5.2. Context-aware Information Server Update Algorithm Measurements

The main goal of the CISUA is to prevent the network flooding with signalling messages from the PoAs when the radio link resources vary. Basically, the PoAs update the CIS with the radio resources information when the resources of the radio access technologies are affected above predefined thresholds. Therefore, since the CIS directly affects the target radio access network decision, it is important to evaluate if the resources availability information stored in the CIS does not affect the TAN selection and the handover decisions. Three different stages can be distinguished based on the available resources information stored on the CIS:

- ***Updated CIS***: the available resources information stored on the CIS is exactly the same as the one stored on the PoA;
- ***Non-Critical CIS***: the available resources information stored on the CIS is different from the one stored on the PoA; however, this difference does not affect the target network handover selection;
- ***Critical CIS***: the available resources information stored on the CIS is different from the one stored on the PoA; in this case, the target network selection and the handover procedure are affected by this difference.

7.5.2.1. Simulated Scenario and Tests Methodology

This section presents a set of simulations to evaluate the impact of the information stored on the CIS during the handover procedure, as well as the impact of the CIS signalling messages on the network performance. The implemented scenario, illustrated in Figure 6-18, is loaded with random network users with an arrival rate according to a Poisson distribution. Each user accesses the network through one of the available PoAs and initiates either a VoIP or an IPTV service. This procedure triggers the CISUA through variations in the available resources in each PoA. The simulation runs for 100 seconds, with 400 users accessing the network.

7.5.2.2. Results

Figure 7-13 and Figure 7-14 illustrate the CISUA performance for Wi-Fi and WiMAX ANs, respectively. The available resources information stored on the PoA (*blue line*) and on the CIS is depicted, as well as its variation while users, randomly distributed, access the network. Two different approaches were implemented for the CISUA:

- ***Conservative*** (*red line*): stringent thresholds are defined to update more frequently the CIS; the information stored on the CIS will be very close to the real available resources on the PoA and therefore increase the successful handover decisions; the drawback is the signaling overhead on the network;
- ***Non-conservative*** (*green line*): flexible thresholds are defined triggering less-frequent update messages from the PoAs to the CIS; the CIS information might be outdated, without compromising, in most cases, the handover decisions; this approach causes less signaling overhead on the network.

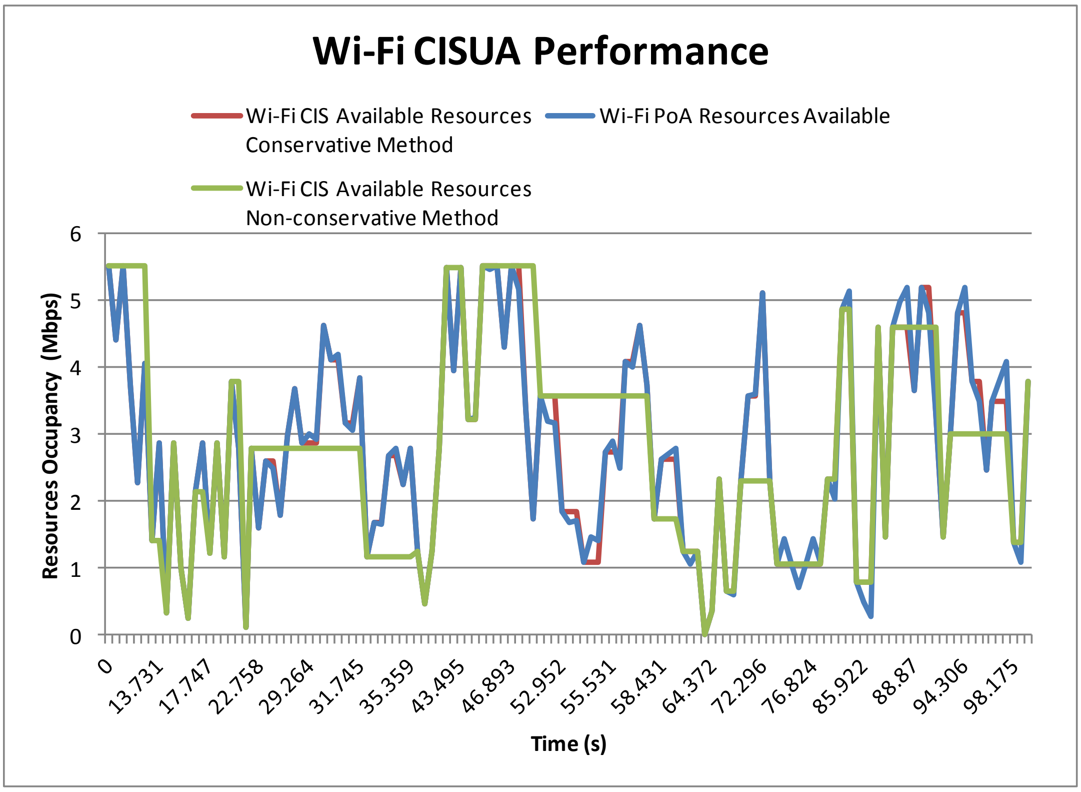

Figure 7-13: Wi-Fi CISUA Performance

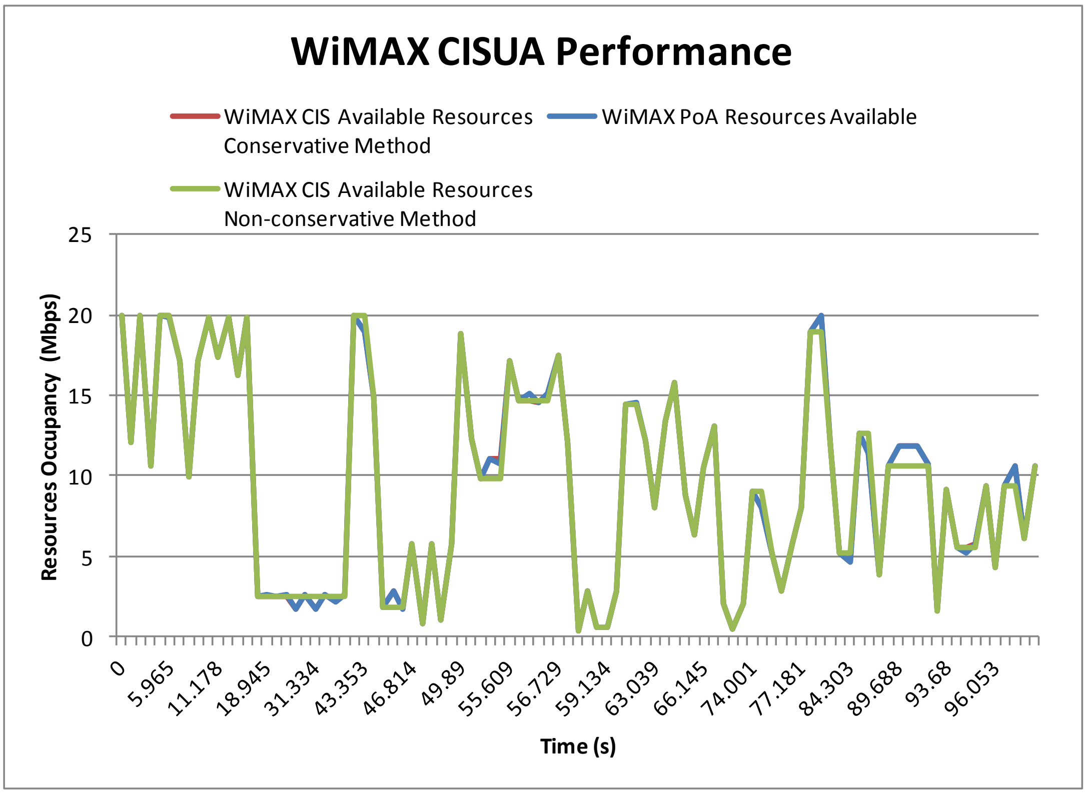

Figure 7-14: WiMAX CISUA performance

Table 7-3 depicts the algorithm performance during a handover procedure for each one of the approaches – based on Figure 7-13 and Figure 7-14. With the *Conservative* method, for most part of the handovers, the available resources information in the CIS is the same as in the PoAs (*Updated CIS* – 57 % for Wi-Fi and 89 % for WiMAX) and therefore the target network selection decision is correct. A shorter set of handovers occurs when the resources information stored in the CIS is different from the one stored on the PoAs (*Non-Critical CIS* – 43 % for Wi-Fi and 11 % for WiMAX). However, this is not critical since the target network selection is correct and the MN obtains the required resources after the handover. The CISUA *Conservative* method has no handovers occurring within the *Critical CIS* stage, therefore preventing any handover failure.

Table 7-3: CISUA performance during a handover procedure

CISUA Method	Updated CIS		Non-Critical CIS		Critical CIS	
	Wi-Fi	WiMAX	Wi-Fi	WiMAX	Wi-Fi	WiMAX
Non-Conservative	39 %	52 %	55 %	43 %	6 %	5 %
Conservative	57 %	89 %	43 %	11 %	0 %	0 %

For the *Non-Conservative* method, the handovers are distributed along the three CIS stages (*Updated*, *Non-Critical* and *Critical*). Therefore, this approach may lead to wrong decisions (6 % for Wi-Fi and 5 % for WiMAX) on the TAN selection, that is, handover requests might be rejected within this stage.

Finally, Table 7-4 depicts the number of update messages sent by the PoA to the CIS. As expected, for the *Conservative* method, both Wi-Fi and WiMAX access technologies send a higher number of messages (0.75 / sec for Wi-Fi and 0.74 / sec for WiMAX) to the CIS.

It is also important to mention that, for the *Non-Conservative* method, approximately 25 % of the PoA resources variations trigger an update message to the CIS, whereas for the *Conservative* method, approximately 40 % of the resources variations originate an update message from the PoA to the CIS.

Table 7-4: Number of update messages triggered by CISUA

Access Technology	CIS Update Messages per second	
	Non-Conservative	Conservative
Wi-Fi	0.41	0.75
WiMAX	0.64	0.74

Based on the presented results, it is shown that the CISUA optimizes the handover preparation phase, minimizing wrong TAN decisions, as well as minimizing the network flooding with update messages.

7.6. Summary

This section proposed the concept of a CIS in the 802.21 framework. Through this concept, the MIIS IS is able to collect and store information about the available network technologies. This information will be provided to help on the handover preparation process, reducing the time to perform, only in one phase, the *CANs Discovery* and the *CANs Resources Availability Check* phases. To avoid the network flooding with signaling messages from the PoAs to the CIS when the radio resources vary, the CISUA was designed, implemented and evaluated. Basically, the PoAs update the CIS with the radio resources information when the resources of the radio access technologies are affected above predefined thresholds. Therefore, since the CIS directly affects the target radio access network decision, a simulation-based evaluation of the algorithm was made to check the impact of the information stored on the CIS during the handover procedure, as well as the impact of the CIS signalling messages on the network performance. The obtained result demonstrated that the CISUA optimizes the handover preparation phase, minimizing wrong TAN decisions, as well as minimizing the network flooding with update messages. To support this concept, several extensions were proposed to the IEEE 802.21 framework, combining both the support of new update messages and the state machines to handle these messages and their extensions. The results obtained from the simulation of the proposed framework show that the differences between the static IS and the CIS are significant, since with the CIS, the MNs do not need to query every possible CAN. These performance enhancements are shown in the several handovers, between Wi-Fi, WiMAX and UMTS networks.

8. Conclusion

Bearing in mind the increasing trend of mobile devices adoption, BWA technologies will play a dominant role in NGNs. Following this trend, the main objective of this Thesis was twofold. The first one was to **understand the impact of integrating the WiMAX technology in a NGN environment**, characterized by the seamless delivery of multimedia services with QoS constraints. Subsequently, continuing the work developed for the WiMAX technology, the second major objective of this Thesis was to **provide seamless mobility solutions enhanced with QoS and context information procedures in heterogeneous access environments** comprised by the Wi-Fi, WiMAX and 3GPP UMTS/HSPA access technologies.

As mentioned above, one of the core objectives of this Thesis was related with WiMAX, one of the most promising access technologies in the mobile telecommunications field, together with 3GPP LTE. For the fixed broadband wireless communications, fixed WiMAX (technically IEEE 802.16d) is the only pure fixed standard for BWA communications and therefore is clearly taking the lead. On the other hand, in what mobile broadband telecommunication scenarios are concerned, WiMAX and LTE are competing together for the best market position. According to studies carried out by the WiMAX Forum, as of May 2011, there were 583 WiMAX deployments around the world in 150 separate regional market areas. These numbers are illustrated in Table 8-1.

Table 8-1: WiMAX deployments and customers per region [221]

Region	Deployments	Countries	Customers
Central and Latin America	120	33	87.347.832
Africa	117	43	322.666.970
Asia-Pacific	98	23	117.846.830
Eastern Europe	86	21	102.503.669
Western Europe	77	18	33.509.544
North America (USA and Canada)	56	2	127.000.000
Middle East	29	10	32.526.407
Total	**583**	**150**	**823.401.252**

Although the majority of countries have deployed both fixed and mobile WiMAX networks, the number of fixed WiMAX networks still outnumbers the deployments with mobility support roughly by twice.

However, recent market data indicate that the large telecommunication operators opt for protecting their past investments in 3GPP technologies and line behind 3GPP's LTE access technology. Fixed WiMAX deployments serving as last-mile links instead of wired connections in scarcely populated areas might be the main target for WiMAX in the highly developed markets of North America and Western Europe. That is, key telecommunications players are considering WiMAX mainly as a fixed broadband replacement technology, for certain deployment areas, as it can provide broadband access at a fraction of the cost of an equivalent wired broadband alternative. On the other hand, there is still great room for developing a modern telecommunication infrastructure in Asia, Eastern Europe, South America and Africa, where new operators may be able to take on the market opportunities by deploying fixed and mobile WiMAX systems.

Figure 8-1 illustrates the fixed (in red) and mobile (in blue) WiMAX deployments around the world in May 2011.

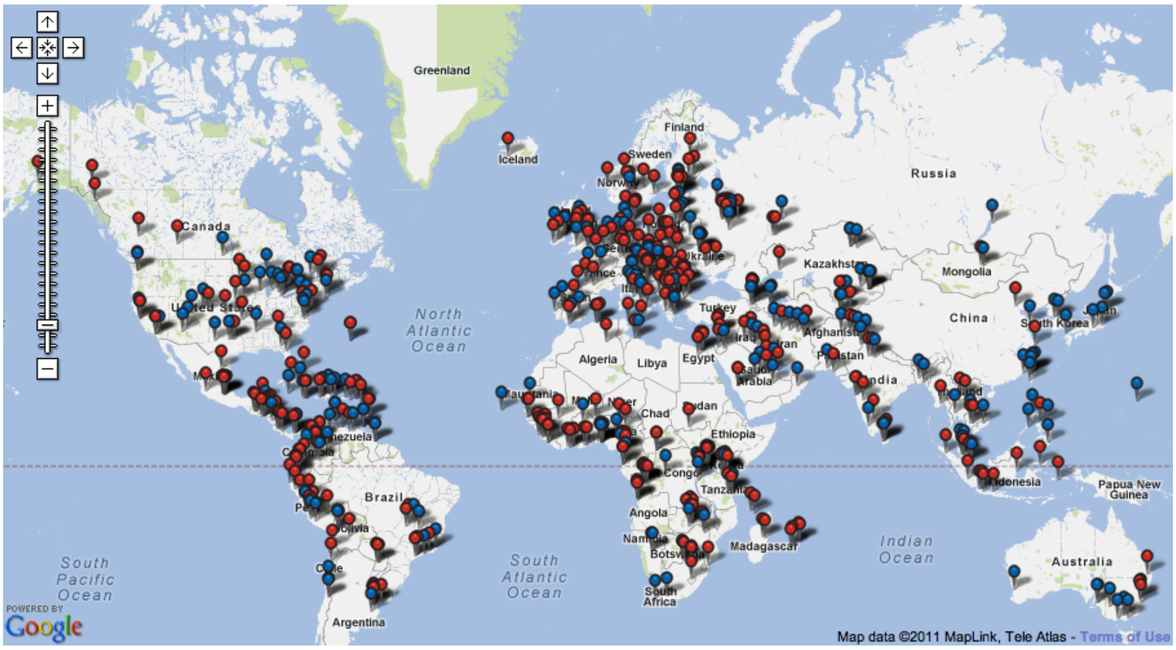

Figure 8-1: Fixed and mobile WiMAX deployments worldwide [221]

With an IP-based infrastructure, WiMAX offers an alternative way to deploy wireless broadband networks with mobility support which is directly comparable to the latest 3GPP-standardized technologies that dominate current cellular network deployments. In particular, Russia and India have recently been active in planning and deploying new mobile networks which will employ WiMAX to address the lack of sufficient wired infrastructure which has been the main obstacle in providing affordable broadband access. At this moment, it is predictable that WiMAX is well positioned in technical terms to play a major role in future developments, but dominance is far from guaranteed.

8.1. Results and Achievements

In order to provide a set of motivating use-cases for this Thesis, an overview of the most relevant scenarios was given. The scenarios focused mainly on 4G wireless access technologies, more specifically on WiMAX and LTE. Fixed, mobile, relay, backhaul and mesh topologies were considered in both urban and rural environments. Seamless inter-technology handover scenarios were also addressed, either driven by the imminent loss of connectivity or motivated by network resources optimization. From the applications point of view, both telemedicine and environmental applications were considered. For the telemedicine scenarios, which mainly involve mobile access, both mobile WiMAX and LTE access technologies are potentially very interesting solutions. With respect to the environmental monitoring scenarios, it was proven, through a real fire prevention deployment in Portugal, that fixed WiMAX access technology is a very interesting solution and therefore should be considered as serious candidate for fixed broadband access environments.

Thereafter, in order to address the first major objective of the Thesis, an end-to-end WiMAX architecture, focusing on QoS provisioning mechanisms for resources request signaling and reservation, was specified. SIP-based multimedia applications, as well as legacy applications, are supported and integrated with the architecture. To interact with the WiMAX access technology, a cross-layer framework was defined, providing the higher layers with mobility, QoS and network management services. By integrating a set of standardized interfaces, such as SNMP, telnet and WiMAX Forum R6, among others, the cross-layer framework was able to communicate with any type of WiMAX system. The proposed architecture, specifically the cross-layer framework, was evaluated through a real prototype deployment with a WiMAX equipment from Redline Communications. The WiMAX cross layer signaling processing times are approximately 15 ms, even for 200 VoIP background flows simultaneously injected in the WiMAX link, indicating that the proposed cross-layer architecture is efficient and able to support real-time services.

Afterwards, still focused on the WiMAX access technology, a set of extensions is proposed to streamline this technology with seamless mobility procedures. The developed extensions are built on top of the 802.21 framework, integrating mobility and QoS procedures. The proposed architecture enhances the mobility mechanisms in WiMAX access networks and is appropriate to address scenarios with real-time applications. The architecture integrates QoS functionalities, specifying mechanisms to enable the complete combination of mobility and QoS, using an extension of the NSIS protocol with IEEE 802.21 information. A demonstrator was developed to evaluate the WiMAX handovers performance in a concatenated scenario with Wi-Fi. The obtained results indicate the handover effect in the application flows is not noticeable, as all the process is prepared beforehand, and QoS is established in the new WiMAX network.

With respect to the second major objective of this Thesis, the scope of the developed work was broaden in order to study QoS and mobility management procedures in heterogeneous wireless access environments. A mobility heterogeneous architecture was proposed, comprising Wi-Fi, WiMAX and 3GPP based access networks (UMTS/HSPA and LTE). The architecture supports mobility procedures through MIP, and is further extended to support 802.21 services. A method for managing radio resources in the radio access technologies during a handover procedure through the 802.21 framework is proposed. The proposed 802.21 primitives allow an application level entity, such as a RM, to enforce radio resources allocation and deletion in the access technologies, either locally or remotely, as well as to receive event notifications from the link layer technologies with the resources reservation and/or deletion result. To validate the described mechanisms in a large-scale environment, simulations were developed on NS-2 platform for handover mechanisms between WiMAX, Wi-Fi and 3GPP UMTS. Through the obtained results, it is possible to conclude that the 802.21 brings significant advantages regarding seamless mobility, if properly improved and applied to the specific technologies. Furthermore, it was discussed and presented a solution to achieve heterogeneous mobility in a real network scenario, composed by a commercial 3GPP UMTS/HSPA network, WiMAX and Wi-Fi, as well as an Android smartphone, taking advantage on the recent 802.21 developments. The results have clearly showed that under the proposed solution the handover delay and packet loss are significantly lower than the ones resulting from the normal operation of a unmodified MIPv6 implementation (where the handover only occurs when the current connection is lost – *break before make* approach).

Finally, bearing in mind the increasing importance given to contextual information, the final objective was to improve the handover decision-making processes in heterogeneous access environments through the integration of context information from both the network elements and the end user. Towards this goal, a Context-aware Information Server (CIS) for the IEEE 802.21 framework was proposed. Through this concept, the IS from the 802.21 MIIS is able to collect and store information about the available network technologies, optimizing the handover preparation phase. Simulation results demonstrated that the proposed CIS improves the handover procedure (compared with the standardized static IS). These performance enhancements are shown in the several handovers, between Wi-Fi, WiMAX and UMTS networks.

8.2. Achievements for PTIN

Since this Thesis was developed in an industrial environment, the research work carried out was naturally aligned with the company strategy in the medium and long term. Thus, it is important to highlight the main achievements that this Thesis brought to PTIN.

Two significant achievements related with heterogeneous wireless access networks coexistence were obtained. In particular, a connectivity management product ("MyConnect") and a seamless mobility management pre-product ("MyMove") were developed within the company based on the work made in this Thesis. The following subsections briefly describe these platforms.

8.2.1. Connectivity Management Platform – MyConnect

The "MyConnect" platform manages all the wireless connections of a user's terminal, offering "Always Best Connected" (ABC) transparent connectivity. This allows the terminal to automatically connect to the best available wireless (UMTS/HSPA, LTE, Wi-Fi...) or wired (Ethernet) access network, at any given moment.

In addition to manage automatic connectivity with the various available networks, "MyConnect" also includes an authentication mechanism for Wi-Fi hotspots which is fully seamless for the user. This seamless authentication is based on the the EAP-SIM [222] method, standardised by the IETF, which uses the information stored on the equipment SIM card to authenticate the user on the Wi-Fi network.

From the operator's point of view, and as a complement to the "ABC" connectivity policy, the "MyConnect" platform also includes connectivity policies for offloading the mobile broadband networks (UMTS/HSPA, LTE) to Wi-Fi networks. Given the increasing shortage of resources in the mobile networks and the proliferation of Wi-Fi hotspots, automatic offloading to the later enables operators to optimise the radio resources usage of these networks and, simultaneously, to make the most of their Wi-Fi hotspots, while using an authentication mechanism that is seamless to the user.

To enable the interaction with the user, a user-friendly graphical user interface is provided by the "MyConnect" application enabling the control of the wireless connections and the data traffic consumption. Figure 8-2 illustrates the "MyConnect" application user interface, split in three main parts, each one dedicated to a specific access technology connectivity status and definitions: "Mobile Broadband" (or 3G/4G), "Wi-Fi" and "Local Area" (or Ethernet).

The selection of the best access network at a particular moment is one of the most important features of the "MyConnect" application. To this end, the application comes supplied with two operating modes: "Automatic Management Mode" and "Manual Management Mode". In the "Automatic Management Mode" the application automatically controls all the procedures involved in connecting the user to the Internet, freeing the user from any need to configure or control the application. In order to manage these connectivity processes automatically, a set of policies are configured in the application, including:

- **3G Offload**: this policy automatically connects the mobile terminal to Wi-Fi networks, whenever these are available (thus freeing up 3G mobile networks);
- **Minimum Cost**: this policy ensures that the user is connected to the lowest cost access network, using the following priority order: Ethernet, Wi-Fi and 3G;
- **Permanent Access (Always Best Connected)**: this policy ensures that the user is always connected to the Internet, wherever there are access networks available. Thus, if any access network becomes inaccessible (e.g. when the user moves around and the connection to the Wi-Fi wireless network is lost), the application immediately tries to connect to the access network with the next highest priority on the priority list.

In the "Manual Management Mode" the user controls and configures the application and may choose, at any given time, which access network to connect to.

Figure 8-2: "MyConnect" application user interface

Note that this product was already trialed in several national and international network operators from three continents (South America, Europe and Asia).

8.2.2. Mobility Management Platform – MyMove

One of the most important companies of the PT Group is the mobile operator (also known as TMN [210]), which has approximately 7 millions of subscribers in Portugal. TMN has a strong commitment with the 3GPP radio access technologies, especially with UMTS, HSPA and the upcoming LTE, but it also has a strong market in wireless local access networks – Wi-Fi. Moreover, new handsets, or smart-phones, are being delivered in the Portuguese market. Some of these new handsets are produced in partnership between TMN and the Asian manufacturers, such as ZTE and Huawei (e.g. Google Android based mobile phones). Therefore, there is a good opportunity to provide new functionalities and added-value services on these handsets. One of the most important features is to provide ubiquitous access to the subscribers, independently of their location, radio access technology and service. With respect to the services, it is important to mention that one of the most successful services provided by the PT Group nowadays is the IPTV service. The PT IPTV service, designated as MEO [223], can be distributed in fixed environments, using fiber and DSL lines, or in mobile environments, using the TMN mobile access technologies (also known as MEO Go [224]). With this type of services available, it is very important to provide the subscribers with ubiquitous access to these services, which means that they should be able to access their subscribed IPTV channels independently of their location (terminal mobility – @home, @bus, @park, …) and access device (session mobility – @smart-phone, @TV, …).

The development of this Thesis has provided PTIN with the required knowledge and skills about seamless mobility procedures in heterogeneous environments. This means that a strong knowledge acquisition on the radio access technologies, such as WiMAX, 3GPP HSPA/LTE and Wi-Fi, and how these technologies can be integrated in a next generation network environment, including QoS and mobility mechanisms, was obtained within the Thesis activities. More specifically, on the mobility mechanisms area, it was possible to obtain significant skills and knowledge on the IEEE 802.21 MIH framework, which is probably the most promising platform to optimize the mobility procedures in heterogeneous access environments. In this context, the output of the Thesis is already being used to leverage and to provide the required mobility-related functionalities within the PTIN solutions. Specifically, it is being evaluated the integration of the IEEE 802.21 MIH platform in the PT framework in order to optimize and deliver added-value services to the subscribers seamlessly. The most promising example is the distribution of the PT IPTV services (MEO Go service) in an heterogeneous environment. Special focus was given to two specific functionalities of the 802.21 framework:

- IEEE 802.21 MIIS: dynamic capabilities were proposed to the IEEE 802.21 IS in order to support context information from the customers and the network, and thereby optimize the vertical handover decision algorithms [218];
- IEEE 802.21 MICS: a modification to the IEEE 802.21 framework in order to integrate QoS enforcement in the radio access technologies during the handover preparation phase was proposed. PTIN, in collaboration with National Centre for Scientific Research Demokritos [225] and University of Aegean [226], has submitted a patent “Managing Link Layer Resources for Media Independent Handover“ on this subject to the WIPO (World Intellectual Property Organization) [191].

In order to proceed with the internal adoption of the Thesis results, an IPv6 oriented mobility prototype with Android smartphones, which provides seamless handovers between Wi-Fi/WiMAX and the commercial 3G UMTS/HSPA access network from TMN was developed. IEEE 802.21 framework was integrated in the prototype to enhance the mobility procedures in the heterogeneous access environment. Further details about the seamless mobility mechanisms of the testbed are described in sections 6.3 and 6.6.

The seamless mobility prototype, illustrated in Figure 8-3, designated "MyMove", was demonstrated with great success to PTIN potential customers in national and international events [227] [228] [229]. As a result of this success, the prototype is in a pre-product phase, that is, it is currently being integrated with other PTIN control platforms. The forecast for the provision of a commercial product resulting from this prototype is for the end of 2012 or beginning of 2013.

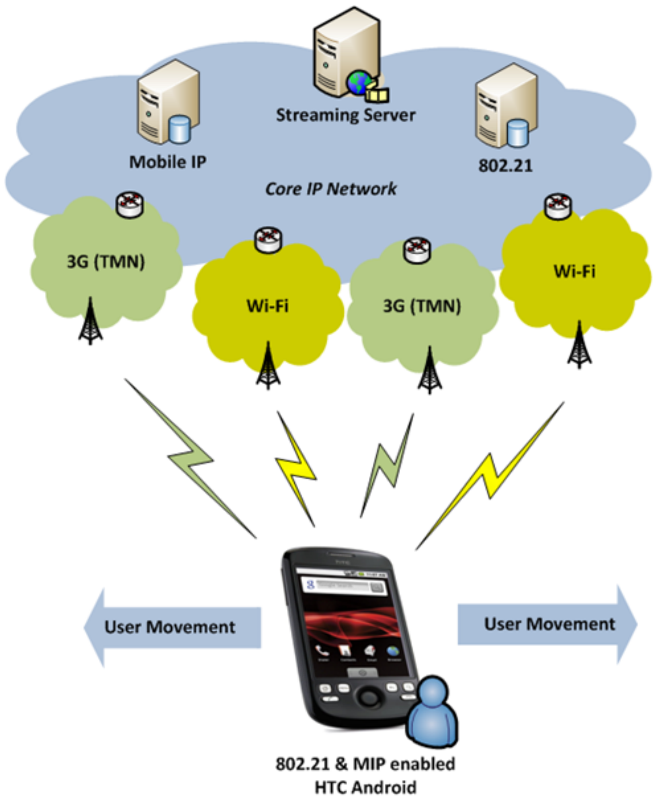

Figure 8-3: PTIN “MyMove” demonstrator

Figure 8-4 illustrates the Android smartphone mobility control interface. The features provided by this graphical interface are the following:

- Start/stop IEEE 802.21 services (MIHF, Android Mobility Manager – AMM, Android Interface Manager – AIM UMTS/HSPA and AIM Wi-Fi);
- Information about the current state of the IEEE 802.21 services (MIHF, AMM, AIM UMTS/HSPA and AIM Wi-Fi);
- Information about the current interface in use by MIPv6;
- Trigger handovers to Wi-Fi and/or UMTS/HSPA on the MN side;
- Trigger handovers to Wi-Fi and/or UMTS/HSPA on MIPv6 (only for testing).

Figure 8-4: "MyMove" Android (HTC Google Nexus One) control interface

Figure 8-5 shows a video streaming being received by the Android. In the screen is displayed a notification that informs the user that there was a handover from UMTS/HSPA to Wi-Fi. This notification informs the user if the handover was completed or failed.

Figure 8-5: "MyMove" Android (HTC Google Nexus One) user interface – handover from 3G to Wi-Fi

This demonstrator was selected as one of the showcases in the “Mobile Innovation Day” event (Figure 8-6), organized by the PT Group and the most important LTE manufacturers in the mobile market: Alcatel-Lucent, Nokia Siemens Network, Ericsson and Huawei.

hoje é notícia
22/04/2010

PT INOVAÇÃO

PT Inovação palco da apresentação de serviços de 4ª Geração Móvel

Zeinal bava, Presidente Executivo da PT, apresentou na PT Inovação, em Aveiro, diversas experiências de futuro, associadas a serviços de 4ª geração. O Mobile Innovation Day, que se realizou nas instalações da PT Inovação, pretendeu demonstrar as potencialidades da tecnologia LTE (Long Term Evolution), considerada uma “tecnologia verde”, que permite uma maior eficiência da utilização do espectro radioeléctrico e equipamentos com uma maior eficiência energética.

A PT tem investido nesta tecnologia e está já previsto para o segundo semestre de 2010 um projecto-piloto pioneiro de implementação da rede 4G, virá introduzir velocidades de banda larga móvel de 100 a 150 Mbps já em 2011.

A PT Inovação não só acolheu o evento como marcou presença com o projecto PT Teleaula e a solução de teleconsulta Medigraf, que demonstrou que no futuro será possível em mobilidade, numa ambulância, por exemplo, enviar exames médicos para os hospitais. Alcino Lavrador, presidente executivo da PT Inovação, apresentou ainda a solução Meo Vital que possibilita o envio de informação sobre o ritmo cardíaco via telemóvel para o MEO, com recurso ao VitalJacket (uma t-shirt que permite monitorizar os sinais vitais, desenvolvida pela Biodevices). De mencionar também a presença de projectos como Creative Learning 3D, demonstrador da inovação ao serviço da formação em novos contextos, Context Aware Content Distribution e Seamless IPV6, projectos onde se desenvolvem competências ao nível do handover das redes móveis sem perda da qualidade de serviço.

Neste Mobile Innovation Day estiveram ainda presentes empresas como a Nokia Siemens Networks, Huawei, Ericsson e Alcatel-Lucent, que apresentaram as suas soluções tecnológicas de transmissão para a chamada quarta geração.

Figure 8-6: PT Group “Mobile Innovation Day” event

Finally, another potential achievement from the activities carried out in this Thesis is related with the WiMAX technology and, more specifically, its integration with the network operator all-IP platform. With regard to this outcome, a prototype was installed in PTIN premises with potential to be integrated with the PTIN Operational and Support Systems (OSSs). Once the integration is initiated, the development carried out within the framework of this Thesis will be useful, both from a theoretical point of view (using the acquired knowledge) and from the experimental perspective (using the practical experience obtained through the WiMAX testbed).

8.3. Future Work

One of the open issues to be studied in the short-term is the evaluation (through implementation and/or simulation) of the proposed mobility enhancements in wireless access environments involving the **LTE** access technology. This evaluation was not made on the scope of this Thesis due to the lack of infrastructures. Apart from assessment of the LTE technology in heterogeneous mobile environments, and given the constant evolution of wireless access technologies, another aspect to study in the near future is the impact of **LTE-Advanced and IEEE 802.16m**, also known as **WiMAX2.0**, access technologies in the proposed seamless mobility procedures. These technologies were elected by the ITU as “the access technologies” for 4G, and it is expected that they become available for network operators rollout after 2015.

Another relevant topic that should be addressed in the near future is related to the use of a standardized core network for global support, integration and coexistence of multiple existing wireless networks. Thus, it is guaranteed the access networks separation and independence from the mobile core network, with the provision of QoS and mobility mechanisms. Following this trend, the 3GPP standardization body has defined the **Evolved Packet Core (EPC)**, which objective is precisely to unify and bring together the functionalities to control the various access networks, while allowing integration with

IMS service platforms and the Internet. The EPC will allow the coexistence of 3GPP access networks, such as UMTS/HSPA and LTE, as well as IEEE based access networks, such as WiMAX and Wi-Fi.

In a future marked by the customization and adaptation of services available to the user, it is fundamental for the operator, as a service provider, to have the accurate perception of the user “situation” (i.e. surroundings, movement, location, preferences, type and capabilities of the terminal), as well as of the network conditions (i.e. access network types, availability, throughput). Therefore, it is very important to optimize the mechanisms related to the management and control of mobility procedures with **context information platforms**. This topic was addressed on this Thesis, through the integration of information about the resources available in multiple access networks. The next step is to integrate other context information, as well as context information platforms and assess the impact on heterogeneous access environments.

Another trend is to enable the simultaneous use of multiple radio access interfaces of the mobile devices. This concept, known as **multihoming**, allows the user to access the Internet through more than one interface and therefore maximize the available bandwidth for the applications. A typical use-case is for mobile video delivery using the Wi-Fi and LTE interfaces of the mobile device: to maximize the video quality, the network may use both LTE and Wi-Fi interfaces to simultaneously deliver the video frames to the terminal. This requires an appropriate video codec, such as Scalable Video Coding (SVC), in order to split the video in different layers, according to the video resolution. The low resolution video layers are delivered on the most robust access interface (e.g. LTE), guaranteeing that the a low resolution sample of the video is delivered to the user, whereas the high resolution video layers are delivered on the other access technology interface (e.g. Wi-Fi).

Another open topic that requires further study is related with **flow mobility**. That is, not all services that are delivered to the end user require seamless mobility. For example, viewing email or web browsing does not require seamless handover. Only real-time services, such as voice and video, usually require IP mobility without service disruption. Thus, it is important to enable seamless mobility management mechanisms only for services that do not tolerate service disruption, while using legacy connectivity procedures for the services that do not require seamless mobility.

Finally, a crucial topic that should also be addressed in the future is related with **energy-aware mobility mechanisms**. More precisely, in wireless environments, in which mobile devices have battery limitations, energy savings are essential. Thus, energy-aware mobility procedures are required to optimize the use of radio interfaces according to the energy expenditure of each one of them.

References

[1] ITU-T, "General Overview of Next Generation Networks", *ITU-T Rec. Y.2001*, December 2004.

[2] ITU-T, "General Principles and General Reference Model for Next Generation Networks", *ITU-T Rec. Y.2011*, October 2004.

[3] ITU-T, "Functional Requirements and Architecture of the Next Generation Networks", *ITU-T Rec. Y.2121*, September 2006.

[4] ITU-T, http://www.itu.int/ITU-T/, accessed in 15th January 2012.

[5] IETF, http://www.ietf.org, accessed in 15th January 2012.

[6] IEEE, http://www.ieee.org, accessed in 15th January 2012.

[7] ETSI, http://www.etsi.org, accessed in 15th January 2012.

[8] WiMAX Forum, http://www.wimaxforum.org, accessed in 15th January 2012.

[9] 3GPP, http://www.3gpp.org, accessed in 15th January 2012.

[10] 3GPP SA, "IP Multimedia Subsystem (IMS) – Stage 2", *TS 23.228, v11.3.0, Release 11*, December 2011.

[11] J. Rosenberg, H. Schulzrinne, G. Camarillo, A. Johnston, J. Peterson, R. Sparks, M, Handley, E. Schooler, "SIP: Session Initiation Protocol", *IETF RFC 3261*, June 2002.

[12] Cisco Virtual Networking Index: Global Mobile Data Traffic Forecast Update, 2010 – 2015, http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-520862.html, accessed in 15th January 2012.

[13] ITU-R, "Framework and Overall Objectives of the Future Development of IMT-2000 and Systems Beyond IMT-2000", *ITU-R Rec. M.1645*, June 2003.

[14] 3GPP RAN, "UTRAN Overall Description", *TS 25.401, v10.2.0, Release 10*, June 2011.

[15] 3GPP RAN, "HSDPA Overall Description – Stage 2", *TS 25.308, v6.4.0, Release 6*, March 2007.

[16] IMT-Advanced, http://www.itu.int/ITU-R/index.asp?category=information&rlink=imt-advanced, accessed in 15th January.

[17] 3GPP RAN, "E-UTRA and E-UTRAN Overall Description – Stage 2", *TS 36.300, v11.0.0, Release 11*, December 2011.

[18] 3GPP RAN, "Further Advancements for E-UTRA – LTE-Advanced Feasibility Studies", *TS 36.815, v9.1.0, Release 9*, June 2010.

[19] IEEE 802.16, "IEEE Standard for Local and Metropolitan Area Networks. Part 16: Air Interface for Fixed Broadband Wireless Access Systems", *IEEE Std. 802.16-2004*, October 2004.

[20] IEEE 802.16, “Amendment to IEEE Standard for Local and Metropolitan Area Networks. Part 16: Air Interface for Fixed Broadband Wireless Access Systems – Physical and Medium Access Control Layer for Combined Fixed and Mobile Operation in Licensed Bands”, *IEEE Std. 802.16e-2005*, December 2005.

[21] IEEE 802.16, “IEEE Standard for Local and Metropolitan Area Networks; Part 16: Air Interface for Broadband Wireless Access Systems; Amendment 3: Advanced Air Interface”, *IEEE Std. 802.16m-2011*, May 2011.

[22] IMT-Advanced 4G Technologies, http://www.itu.int/net/pressoffice/press_releases/2012/04.aspx, accessed in 15th January 2012.

[23] IEEE 802.11, “IEEE Standard for Information Technology; Local and Metropolitan Area Networks; Specific Requirements; Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications; Amendment 5: Enhancements for Higher Throughput”, *IEEE Std. 802.11n-2009*, October 2009.

[24] PT Inovação, http://www.ptinovacao.pt/, accessed in 15th January 2012.

[25] FP6 DAIDALOS Project, http://cordis.europa.eu/fetch?CALLER=FP6_PROJ&ACTION=D&DOC=1&CAT=PROJ&RCN=71242, accessed in 15th January 2012.

[26] FP6 DAIDALOS II Project, http://cordis.europa.eu/fetch?CALLER=FP6_PROJ&ACTION=D&DOC=1&CAT=PROJ&RCN=80687, accessed in 15th January 2012.

[27] FP6 WEIRD Project, http://cordis.europa.eu/fetch?CALLER=FP6_PROJ&ACTION=D&DOC=354&CAT=PROJ&QUERY=01289b2026e6:f47e:25f2e25b&RCN=79418 , accessed in 15th January 2012.

[28] FP7 HURRICANE Project, http://cordis.europa.eu/fetch?CALLER=PROJ_ICT&ACTION=D&CAT=PROJ&RCN=85314 , accessed in 15th January 2012.

[29] E. Borcoci et al., “System Specification”, *Deliverable D2.3*, *IST-034622-IP WEIRD*, May 2007.

[30] R. Braden, D. Clark, S. Shenker, “Integrated Services in the Internet Architecture: An Overview”, *IETF RFC 1633*, June 1994.

[31] S. Blake, D. Black, M. Carlson, E. Davies, Z. Wang, W. Weiss, “An Architecture for Differentiated Services”, *IETF RFC 2475*, December 1998.

[32] R. Hancock, G. Karagiannis, J. Loughney, S. Van den Bosch, “Next Step In Signaling (NSIS): Framework”, *IETF RFC 4080*, June 2005.

[33] J. Manner, G. Karagiannis, A. McDonald, “NSIS Signaling Layer Protocol (NSLP) for Quality of Service (QoS) Signaling”, *IETF RFC 5974*, October 2010.

[34] H. Schulzrinne, R. Hancock, "GIST: General Internet Signaling Transport", *IETF RFC 5971*, October 2010.

[35] C. Perkins, "IP Mobility Support for IPv4", *IETF RFC 3220*, January 2002.

[36] D. Johnson, C. Perkins, J. Arkko, "Mobility Support in IPv6", *IETF RFC 3775*, June 2004.

[37] R. Koodli, "Fast Handover for Mobile IPv6", *IETF RFC 4068*, July 2005.

[38] S. Gundavelli, K. Leung, V. Devarapalli, K. Chowdhury, B. Patil, "Proxy Mobile IPv6", *IETF RFC 5213*, August 2008.

[39] IEEE 802.21, "IEEE Standard for Local and Metropolitan Area Networks: Media Independent Handover Services", *IEEE Std. 802.21-2008*, December 2008.

[40] J. Case, M. Fedor, M. Schoffstall, J. Davin, "Simple Network Management Protocol (SNMP)", *IETF RFC 1157*, May 1990.

[41] IEEE 802.16 WG, "IEEE Standard for Local and Metropolitan Area Networks: Part 16: Air Interface for Fixed Broadband Wireless Access Systems; Amendment 3: Management Plane Procedures and Services", *IEEE Std. 802.16g-2007*, December 2007.

[42] WiMAX Forum NWG, "WiMAX Forum Network Architecture: Architecture Tenets, Reference Model and Reference Points, Base Specification", *WMF-T32-001-R016v01*, Release 1.6, Version 0.1, November 2010.

[43] IEEE 802.11, "IEEE Standard for Information Technology; Local and Metropolitan Area Networks; Specific Requirements; Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications; High-Speed Physical Layer in the 5 GHz Band", *IEEE Std. 802.11a-1999*, October 1999.

[44] IEEE 802.11, "IEEE Standard for Information Technology; Local and Metropolitan Area Networks; Specific Requirements; Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications; High-Speed Physical Layer Extension in the 2.4 GHz Band", *IEEE Std. 802.11b-1999*, October 1999.

[45] IEEE 802.11, "IEEE Standard for Information Technology; Local and Metropolitan Area Networks; Specific Requirements; Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications; Amendment 4: Further High Data Rate Extension in the 2.4 GHz Band", *IEEE Std. 802.11g-2003*, June 2003.

[46] IEEE 802.11, "IEEE Standard for Information Technology; Local and Metropolitan Area Networks; Specific Requirements; Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications; Amendment 8: Medium Access Control (MAC) Quality of Service Enhancements", *IEEE Std. 802.11e-2005*, November 2005.

[47] IEEE 802.1, "IEEE Standard for Local and Metropolitan Area Networks; Media Access Control (MAC) Bridges", *IEEE Std. 802.1D-2004*, June 2004.

[48] D. Niyato, E. Hossain, “Call Admission Control for QoS Provisioning in 4G Wireless Networks: Issues and Approaches”, *IEEE Network Magazine, Volume 19, Issue 5*, October 2005, pp. 5 – 11, ISSN: 0890-8044.

[49] S. Marwaha, J. Indulska, M. Portmann, “Challenges and Recent Advances in QoS Provisioning, Signaling, Routing and MAC Protocols for MANETs”, *Telecommunications Networks and Applications Conference (ATNAC)*, February 2009, pp. 97 – 102, ISBN: 978-1-4244-2602-7.

[50] ITU-T Recommendation, “Terms and Definitions Related to Quality of Service and Network Performance Including Dependability”, ITU-T Standardization Sector, ITU-T E.800, 1994.

[51] M. Marchese, “QoS over Heterogeneous Networks”, John Wiley & Sons, April 2007, ISBN: 978-0470017524.

[52] F. Karam, T. Jensen, “A Survey on QoS in Next Generation Networks”, International Journal of Research and Innovation, Advances in Information Sciences and Service Sciences (AISS), Volume 2, Issue 4, February 2011, pp. 91 – 102, ISSN: 1976-3700.

[53] EuQoS Project, http://www.c-lab.de/en/research-projects/completed-research-projects/euqos/index.html, accessed in 15th January 2012.

[54] M. Carmo, B. Carvalho, J. Silva, E. Monteiro, P. Simões, M. Curado, F. Boavida, “NSIS-Based Quality of Service and Resource Allocation in Ethernet Networks”, *Wired and Wireless Internet Communications (WWIC)*, May 2006, pp.132 – 142, ISBN: 3-540-34023-8.

[55] E. Monteiro, F. Boavida, P. Simões, J. Silva, M. Curado, L. Cordeiro, R. Ribeiro, M. Carmos, J. Zhang, “The Use of COPS and NSIS in the EuQoS Project”, *book chapter in Network Control and Engineering for QoS, Security and Mobility, Springer*, 2007, pp. 159 – 171, ISBN: 978-0-387-49689-4.

[56] X. Masip-Bruin, M. Yannuzzi, R. Serral-Gracia, J. Domingo-Pascual, J. Enriquez-Gabeiras, M. Callejo, M. Diaz, F. Racaru, G. Stea, E. Mingozzi, A. Beben, W. Burakowski, E. Monteiro, L. Cordeiro, “The EuQoS System: A Solution for QoS Routing in Heterogeneous Networks”, *IEEE Communications Magazine, Volume 45, Issue 2*, February 2007, pp. 96 - 103, ISSN: 0163-6804.

[57] E. Mingozzi, G. Stea, M. Callejo, J. Enriquez-Gabeiras, G. García-de-Blas, F. Ramón-Salquero, W. Burakowski, A. Beben, J. Sliwinski, H. Tarasiuk, O. Dugeon, M. Diaz, L. Baresse, E. Monteiro, “EuQoS: End-to-End Quality of Service over Heterogeneous Networks”, *Special Issue of Computer Communications on Heterogeneous Networking for Quality, Reliability, Security, and Robustness, Elsevier, Volume 32, Issue 12*, July 2009, pp. 1355 – 1370, ISSN: 0140-3664.

[58] R. Prior, S. Sargento, D. Gomes, R. Aguiar, “Heterogeneous Signaling Framework for End-to-End QoS Support in Next Generation Networks”, *38th Hawaii International Conference on System Sciences (HICSS)*, Hawaii, January 2005, ISBN: 0-7695-2268-8-9.

[59] S. Sargento, R. Prior, F. Sousa, P. Gonçalves, J. Gozdecki, D. Gomes, E. Guainella, A. Cuevas, F. Fontes, “End-to-end QoS Architecture for 4G Scenarios”, *IST Mobile Summit*, Dresden, Germany, June 2005.

[60] S. Sargento, D. Gomes, A. Matos, R. Aguiar, “QoS Signalling in 4G Scenarios”, *IST Mobile Summit*, Mykonos, Greece, June 2006.

[61] A. Kassler, P. Neves, S. Sargento, R. Aguiar, S. Crisóstomo, “QoS and Multicast-aware Integration of Ad-Hoc Networks with Infrastructure Networks based on 802.11 and 802.16”, *1st IEEE International Conference on Sensor and Ad-Hoc Communications and Networks (SECON)*, California, U.S.A., October 2004.

[62] P. Neves, S. Sargento, R. Aguiar, “Implementation of QoS Support in IEEE 802.16 Access Networks”, *5th Conference on Telecommunications (ConfTele)*, Tomar, Portugal, April 2005.

[63] G. Carneiro, C. García, P. Neves, Z. Chen, M. Wetterwald, M. Ricardo, P. Serrano, S. Sargento, A. Banchs, “The DAIDALOS Architecture for QoS over Heterogeneous Wireless Networks”, *IST Mobile Summit*, Dresden, Germany, June 2005.

[64] P. Neves, S. Sargento, R. Aguiar, “Support of Real-time Services over Integrated 802.16 Metropolitan and Local Area Networks”, *11th IEEE Symposium on Computers and Communications (ISCC)*, Cagliary, Italy, June 2006, pp. 15-22, ISBN: 0-7695-2588-1.

[65] P. Neves, S. Sargento, R. Aguiar, “Design and Experimental Evaluation of QoS and Mobility Support over Integrated 802.16 Metropolitan and Local Area Networks”, *1st WEIRD Workshop on WiMAX, Wireless and Mobility (WWW)*, in *Proc. 5th International Conference on Wired/Wireless Internet Communications (WWIC)*, Coimbra, Portugal, May 2007.

[66] P. Neves, S. Sargento, R. Aguiar, F. Fontes, “Design and Experimental Evaluation of QoS and Mobility Support over Integrated 802.16 MANs and 802.11 LANs”, in *IEEE Vehicular Technology Magazine, Volume 3, Issue 4*, December 2008, pp. 39-47, ISSN: 1556-6072.

[67] S. Sargento, V. Jesus, F. Sousa, F. Mitrano, T. Strauf, C. Schmoll, J. Gozdecki, G. Lemos, M. Almeida, D. Corujo, “Context-aware End-to-End QoS Architecture in Multi-technology, Multi-interface Environments”, *IST Mobile Summit*, Budapest, Hungary, June 2007.

[68] M. Almeida, D. Corujo, S. Sargento, V. Jesus, R. Aguiar, “An End-to-End QoS Framework for 4G Mobile Heterogeneous Environments”, *OpenNet Workshop*, Diegem, Belgium, 2007.

[69] S. Sargento, M. Almeida, D. Corujo, V. Jesus, R. Aguiar, J. Gozdecki, G. Carneiro, A. Banchs, P. Yanez-Mingot, “Integration of Mobility and QoS in 4G Scenarios”, *3rd ACM Workshop on QoS and Security for Wireless and Mobile Networks (Q2SWinet)*, Chania, Crete Island, Greece, October 2007, ISBN: 978-1-59593-806-0.

[70] Y. Han, H. Jang, J. Choi, B. Park, J. McNair, “A Cross-Layering Design for IPv6 Fast Handover Support in an IEEE 802.16e Wireless MAN”, *IEEE Network, Volume 21, Issue 6*, December 2007, pp. 54 – 62, ISSN: 0890-8044.

[71] H. Huang, J. Wu, S. Yang, “A Multiple Cross-Layers Explicit Fast Handover Control Using MIH in 802.16e Networks”, *Wireless and Optical Communications Networks (WOCN)*, June 2008.

[72] V. Bernardo, L. Cordeiro, I. Caramelo, B. Sousa, M. Curado, E. Monteiro, "A Seamless Mobility Scenario for IP over WiMAX", *2nd International Workshop on Future Multimedia Networking (FMN)*, Coimbra, Portugal, June 2009, ISBN: 978-3-642-02471-9.

[73] H. Lee, S. Min, "A Network-based Fast Handover Scheme over IEEE 802.16e Access Networks", *International Symposium on Communications and Information Technology (ISCIT)*, September 2009, Icheon, South Korea, pp. 1084 – 1089, ISBN: 978-1-4244-4521-9.

[74] H. Huang, J. Wu, "A Pre-Binding Update Fast Handover Control Using IEEE 802.21 MIH over 802.16e Networks", *International Conference on Communications and Mobile Computing*, Volume 2, 2009, ISBN: 978-0-7695-3501-2.

[75] J. Yeh, J. Chen, P. Agrawal, "Fast Intra-Network and Cross-Layer Handover (FINCH) for WiMAX and Mobile Internet", *IEEE Transactions on Mobile Computing*, Volume 8, Number 4, April 2009, pp. 558 – 574, ISSN: 1536-1233.

[76] C. Shih, Y. Chen, "A FMIPv6 Based Handover Scheme for Real-Time Applications in Mobile WiMAX", *Journal of Networks*, Volume 5, Number 8, August 2010.

[77] Y. Chen, F. Hsieh, "A Cross Layer Design for Handoff in 802.16e Network with IPv6 Mobility", *Wireless Communications and Networking Conference (WCNC)*, March 2007, pp. 3844 – 3849, ISBN: 1-4244-0658-7.

[78] L. Chen, X. Cai, R. Sofia, Z. Huang, "A Cross-layer Fast Handover Scheme For Mobile WiMAX", *Vehicular Technology Conference (VTC-2007 Fall)*, October 2007, pp. 1578 – 1582, ISBN: 978-1-4244-0263-2.

[79] S. Sim, S. Han, J. Park, S. Lee, "Seamless IP Mobility Support for Flat Architecture Mobile WiMAX Networks", *IEEE Communications Magazine, Volume 47, Issue 6*, June 2009, pp. 142 – 148, ISSN: 0163-6804.

[80] W. Jiao, P. Jiang, Y. Ma, "Fast Handover Scheme for Real-Time Applications in Mobile WiMAX", *IEEE International Conference on Communications (ICC 2007)*, June 2007, pp. 6038 – 6042, ISBN: 1-4244-0353-7.

[81] I. Akyildiz, J. Xie, S. Mohanty, "A Survey of Mobility Management in Next-Generation All-IP based Wireless Systems", *IEEE Wireless Communications Magazine, Volume 11, Issue 4*, August 2004, pp. 16 – 28, ISSN: 1536-1284.

[82] P. Taaghol, A. Salkintzis, J. Iyer, "Seamless Integration of Mobile WiMAX and 3GPP Networks", *IEEE Communications Magazine*, *Volume 46, Issue 10*, October 2008, pp. 74 – 85, ISSN: 0163-6804.

[83] Q. Nguyen-Vuong, N. Agoulmine, G. Doudane, "Terminal-Controlled Mobility Management in Heterogeneous Wireless Networks", *IEEE Communications Magazine, Volume 45, Issue 4*, April 2007, pp. 122 – 129, ISSN: 0163-6804.

[84] A. Oliva, A. Banchs, I. Soto, T. Melia, A. Vidal, “An Overview of IEEE 802.21: Media Independent Handover Services”, *IEEE Wireless Communications Magazine, Volume 15, Issue 4*, August 2008, pp. 96 – 103, ISSN: 1536-1284.

[85] D. Meddour, U. Javaid, N. Bihannic, T. Rasheed, R. Boutaba, “Completing the convergence puzzle: a survey and a roadmap", *IEEE Wireless Communications Magazine, Volume 16, Number 3*, June 2009, pp. 86 – 96, ISSN: 1536-1284.

[86] G. Lampropoulos, A. Salkintzis, N. Passas, “Media-Independent Handover for Seamless Service Provision in Heterogeneous Networks”, *IEEE Communications Magazine, Volume 46, Issue 1*, January 2008, pp. 64 – 71, ISSN: 0163-6804.

[87] L. Eastwood, S. Migaldi, Q. Xie, V. Gupta, “Mobility Using IEEE 802.21 in a Heterogeneous IEEE 802.16/802.11-based IMT-Advanced (4G) Network”, *IEEE Wireless Communications Magazine, Volume 15, Issue 2*, pp. 26 – 34, ISSN: 1536-1284.

[88] A. Pontes, D. Silva, J. Jailton, O. Rodrigues, K. Dias, “Handover Management in Integrated WLAN and Mobile WiMAX Networks”, IEEE Wireless Communications Magazine, Volume 15, Issue 5, October 2008, pp. 86 – 95, ISSN: 1536-1284.

[89] C. Huang, C. Lee, and P. Tseng, “Multihomed SIP-Based Network Mobility Using IEEE 802.21 Media Independent Handover”, *IEEE International Conference on Communications (ICC)*, June 2009, pp. 1 – 5, ISBN: 978-1-4244-3435-0.

[90] J. Baek, D. Kim, Y. Suh, E. Hwang, and Y. Chung, “Network-Initiated Handover Based on IEEE 802.21 Framework for QoS Service Continuity in UMTS/802.16e Networks”, *IEEE Vehicular Technology Conference (VTC Spring)*, Singapore, May 2008, pp. 2157 – 2161, ISBN: 978-1-4244-1644-8.

[91] M. Kim, S. Lee, ‘‘Load Balancing based on Layer 3 and IEEE 802.21 Frameworks in PMIPv6 Networks”, *20th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Tokyo, Japan, September 2009, pp. 788 – 792, ISBN: 978-1-4244-5122-7.

[92] F. Jiadi, J. Hong, and L. Xi, ‘‘User-Adaptive Vertical Handover Scheme Based on MIH for Heterogeneous Wireless Networks”, *5th IEEE International Conference on Wireless Communications, Networking and Mobile Computing (WiCom)*, Wuhan, China, September 2009, pp. 1 – 4, ISBN: 978-1-4244-3692-7.

[93] Q. Mussabbir, W. Yao, Z. Niu, X. Fu, “Optimized FMIPv6 Using IEEE 802.21 MIH Services in Vehicular Networks”, *IEEE Transactions on Vehicular Technology, Volume 56, Number 6*, November 2007, pp. 3397 – 3407, ISSN: 0018-9545.

[94] L. Magagula, H. Chan, “IEEE 802.21-assisted Cross-Layer Design and PMIPv6 Mobility Management Framework for Next Generation Wireless Networks”, *IEEE International Conference on Wireless and Mobile Computing, Networking and Communications (WiMOB)*, Avignon, France, October 2008, pp. 159 – 164, ISBN: 978-0-7695-3393-3.

[95] L. Magagula and H. Chan, ''IEEE 802.21 Optimized Handover Delay for Proxy Mobile IPV6", *IEEE Military Communications Conference (MILCOM)*, San Diego, U.S.A., November 2008, pp. 1 – 7, ISBN: 978-1-4244-2676-8.

[96] K. Taniuchi, Y.Ohba, S. Das, M. Tauil, Y-H Chang, A.Dutta, D. Baker, M. Yajnik, D. Famolari, "IEEE 802.21: Media Independent Handover: Features, Applicability and Realization", *IEEE Communication Magazine, Volume 47, Issue 1*, January 2009, pp. 112 – 120, ISSN: 0163-6804.

[97] Wan-Seon Lim, Dong-Wook Kim, Young-Joo Suh, Jeong-Jae Won, "Implementation and performance study of IEEE 802.21 in integrated IEEE 802.11/802.16e networks", *Computer Communications, Volume 32, Issue 1*, January 2009, pp. 134 – 143, ISSN: 0140-3664.

[98] Jae-Han Seol, Jong-Moon Chung, "IEEE 802.21 MIH based Handover for Next Generation Mobile Communication Systems", *4th International Conference on Innovations in Information Technology (IIT)*, November 2007, pp. 431 – 435, ISBN: 978-1-4244-1840-4.

[99] T. Mosawi, D. Wisely, H. Aghvami, "A Novel Micro Mobility Solution Based on Media Independent Handover and SIP", *64th Vehicular Technology Conference (VTC-2006 Fall)*, Montreal, Canada, September 2006, pp. 1 – 5, ISBN: 1-4244-0062-7.

[100] K. Munasinghe, A. Jamalipour, "An Architecture for Mobility Management in Interworked 3G Cellular and WiMAX Networks", *Wireless Telecommunications Symposium, WTS 2008*, April 2008, pp. 291 – 297.

[101] WiFi/WiMAX Heterogeneous Seamless Handover Demonstration by Intel, http://blogs.intel.com/research/2008/02/wifi_wimax_handover.php, accessed in 31st August 2011.

[102] J. Zuniga, G. Reid, "MIH Case Study", https://mentor.ieee.org/802.21/file/08/21-08-0306-00-0000-mih-case-study.ppt, accessed in 31st August 2011.

[103] C. Prehofer, N. Nafisi, Q. Wei, "A Framework for Context-aware Handover Decisions", *14th IEEE Personal, Indoor and Mobile Radio Communications (PIMRC)*, Beijing, China, September 2003, pp. 2794 – 2798, ISBN: 0-7803-7822-9.

[104] Q. Wei, K. Farkas, C. Prehofer, P. Mendes, B. Plattner, "Context-aware Handover Using Active Network Technology", *Computer Networks, Elsevier, Volume 50, Issue 15*, October 2006, pp. 2855 – 2872, ISSN 1389-1286.

[105] P. Bellavista, A. Corradi, L. Foschini, "Context-aware Handoff Middleware for Transparent Service Continuity in Wireless Networks", *Pervasive and Mobile Computing, Elsevier*, August 2007, pp. 439 – 466, ISSN: 1574-1192.

[106] M. Kassar, B. Kervella, G. Pujolle, "An Overview of Vertical Handover Decision Strategies in Heterogeneous Wireless Networks", *Computer Communications, Elsevier, Volume 31, Issue 10*, June 2008, pp. 2607 – 2620, ISSN: 0140-3664.

[107] Q. Duan, “Applying the Service-Oriented Architecture for Network Discovery and Selection in the Next Generation Wireless Mobile Networks”, *International Conference on Network-Based Information Systems (NBIS)*, August 2009, pp. 380 – 385, ISBN: 978-1-4244-4746-6.

[108] W. Lim, D. Kim, Y. Suh, J. Wo, “Efficient WLAN Discovery Schemes Based on IEEE 802.21 MIH Services in Heterogeneous Wireless Networks”, *IEEE International Global Telecommunications Conference (GLOBECOM), November 2008,* pp. 1 – 5, ISBN: 978-1-4244-2324-8.

[109] A. Mateus, R. Marinheiro, “A Media Independent Information Service Integration Architecture for Media Independent Handover”, 9th International Conference on Networks (ICN), April 2010, pp. 173 - 178, ISBN: 978-1-4244-6083-0.

[110] M. Gavrilescu, V. Andrei, E. Popovici, T. Beganu, R. Nastase, O. Fratu, S. Halunga, “Context-aware Reconfigurable Interoperability for Vertical Handover in Wireless Communications”, *2nd International Conference on Wireless Communications, Vehicular Technology, Information Theory and Aerospace & Electronic Systems Technology (Wireless VITAE)*, February 2011, pp. 1 – 5, ISBN: 978-1-4577-0786-5.

[111] M. Xiong, J. Cao, J. Zhang, “Context-Aware Mechanism for IEEE 802.21 Media Independent Handover”, *20th International Conference on Computer Communications and Networks (ICCCN)*, July 2011, pp. 1 – 6, ISBN: 978-1-4577-0637-0.

[112] W. Ying, Y. Jun, Z. Yun, L. Gen, Z. Ping, “Vertical Handover Decision in An Enhanced Media Independent Handover Framework”, IEEE Wireless Communications and Networking Conference (WCNC), March 2008, pp. 2693 – 2698, ISBN: 978-1-4244-1997-5.

[113] Y. Kim, S. Pack, C. Kang, S. Park, “An Enhanced Information Server for Seamless Vertical Handover in IEEE 802.21 MIH Networks”, Computer Networks, Elsevier, Volume 55, Issue 1, January 2011, pp. 147 – 158, ISSN: 1389-1286.

[114] P. Neves, K. Pentikousis, S. Sargento, M. Curado, P. Simões, F. Fontes, “WiMAX Evolution: Emerging Technologies and Applications”, chapter 3, in *Novel WiMAX Scenarios for Future Broadband Wireless Access Networks*, edited by Marcos D. Katz and Frank H. P. Fitzek, Wiley, January 2009, pp. 45-67, ISBN: 978-0-470-69680-4.

[115] K. Pentikousis, J. Pinola, P. Neves, E. Piri, S. Sargento, “Advances in Computers: Improving the Web”, chapter 4, in *Multimedia Services over WiMAX*, edited by Marvin Zelkowitz, Elsevier, March 2010, pp. 151-222, ISBN: 978-0-12-381019-9.

[116] P. Neves et al., “Scenarios, Business Models and System Requirements (version 1)”, *Deliverable D2.1, IST-034622-IP WEIRD*, September 2006.

[117] P. Neves et al., “Scenarios, Business Models and System Requirements (version 2)”, *Deliverable D2.2, IST-034622-IP WEIRD*, January 2007.

[118] IEEE 802.16, "Amendment to IEEE Standard for Local and Metropolitan Area Networks. Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems – Multi-hop Relay Specification", *IEEE Std. 802.16j-2009*, June 2009.

[119] P. Neves, S. Sargento, R. Aguiar, "Support of Real-time Services over Integrated 802.16 Metropolitan and Local Area Networks", in *Proc. 11th IEEE Symposium on Computers and Communications (ISCC)*, Cagliary, Italy, June 2006, pp. 15-22, ISBN: 0-7695-2588-1.

[120] P. Neves, S. Sargento, R. Aguiar, "Design and Experimental Evaluation of QoS and Mobility Support over Integrated 802.16 Metropolitan and Local Area Networks", *1st WEIRD Workshop on WiMAX, Wireless and Mobility (WWW)*, in *Proc. 5th International Conference on Wired/Wireless Internet Communications (WWIC)*, Coimbra, Portugal, May 2007.

[121] P. Neves, S. Sargento, R. Aguiar, F. Fontes, "Design and Experimental Evaluation of QoS and Mobility Support over Integrated 802.16 MANs and 802.11 LANs", in *IEEE Vehicular Technology Magazine, Volume 3, Issue 4*, December 2008, pp. 39-47, ISSN: 1556-6072.

[122] K. Pentikousis, J. Pinola, E. Piri, F. Fitzek, "An Experimental Investigation of VoIP and Video Streaming over Fixed WiMAX", in *Proc. 6th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks and Workshops (WiOPT)*, Berlin, Germany, March 2008, pp. 8-15, ISBN: 978-963-9799-18-9.

[123] K. Pentikousis, J. Pinola, E. Piri, F. Fitzek, "A measurement study of Speex VoIP and H.264/AVC video over IEEE 802.16d and IEEE 802.11g", in *Proc. 13rd IEEE Symposium on Computers and Communications (ISCC),* Marrakech, Morocco, July 2008, pp. 19-24, ISBN: 978-1-4244-2702-4.

[124] A. Gomes et al., "Handover Reference Scenarios, Requirements Specifications and Performance Metrics", *Deliverable D2.1, IST-216006 HURRICANE*, July 2008.

[125] L. Sarakis et al., "Intermediate Integration of HURRICANE Handover Framework", *Deliverable D5.1a, IST-216006 HURRICANE*, December 2009.

[126] L. Sarakis et al., "Final Integration of HURRICANE Handover Framework at Testing Sites", *Deliverable D5.1b, IST-216006 HURRICANE*, June 2010.

[127] IEEE 802.16, "IEEE Standard for Local and Metropolitan Area Networks; Part 16: Air Interface for Broadband Wireless Access Systems", *IEEE Std. 802.16-2009*, May 2009.

[128] A. Cimmino, C. Mambretti, P. Neves, M. Spada, "E-health Broadband Drivers for WiMAX Extension to Isolated Research Networks", in *Proc. Broadband Europe (BBEUROPE)*, Antwerp, Belgium, December 2007.

[129] G. Martufi, M. Katz, P. Neves, M. Curado, M. Castrucci, P. Simões, E. Piri, K. Pentikousis, "Extending WiMAX to New Scenarios: Key Results on System Architecture and Testbeds of the WEIRD project", in *Proc. 2nd European Symposium on Mobile Media Delivery (EUMOB)*, Oulu, Finland, July 2008.

[130] E. Guainella, E. Borcoci, M. Katz, P. Neves, M. Curado, F. Andreotti, E. Angori, "WiMAX technology support for applications in environmental monitoring, fire prevention and telemedicine", in Proc. *IEEE Mobile WiMAX Sympoium*, Florida, U.S.A., March 2007, pp. 125-131, ISBN: 1-4244-0957-8.

[131] E. Guainella, E. Borcoci, M. Katz, P. Neves, L. Ribeiro, F. Andreotti, E. Angori, A. Cimmino, J. Sá Silva, "Extending WiMAX to Novel and Stringent Wireless Scenarios: An Introduction to the WEIRD Project", in *Proc. BroadBand Europe (BBEUROPE)*, Geneva, Switzerland, December 2006.

[132] F. Andreotti, G. Landi, S. Mignanti, G. Tamea, P. Neves, M. Spada, K. Pentikousis, "WEIRD Testbeds with Fixed and Mobile WiMAX Technology for User Applications, Telemedicine and Monitoring of Impervious Areas", in *Proc. 4th International Conference on Testbeds and Research Infrastructures for the Development of Networks & Communities*, *(TRIDENTCOM)*, Innsbruck, Austria, March 2008, pp. 1-10, ISBN: 978-963-9799-24-0.

[133] S. Mignanti, P. Neves, M. Castellano, V. Augusti, C. Mambretti, F. Andreotti, "WEIRD – Real Use Cases and Applications for the WiMAX Technology", *2nd Broadband Wireless Access Workshop (BWA), in Proc. 6th IEEE Consumer Communications & Networking Conference (CCNC)*, Las Vegas, U.S.A., January 2008, pp. 948-952, ISBN: 978-1-4244-1456-7.

[134] A. Cimmino, C. Mambretti, P. Neves, M. Spada, "E-health Broadband Drivers for WiMAX Extension to Isolated Research Networks", in *Proc. Broadband Europe (BBEUROPE)*, Antwerp, Belgium, December 2007.

[135] P. Neves, P. Simões, A. Gomes, L. Mário, S. Sargento, F. Fontes, E. Monteiro, T. Bohnert, "WiMAX for Emergency Services: An Empirical Evaluation", *1st Broadband Wireless Access Workshop (BWA), in Proc. 1st Next Generation Mobile Applications, Services and Technologies (NGMAST)*, Cardiff, Wales, Great-Britain, September 2007, pp. 340-345, ISBN: 0-7695-2878-3.

[136] Iperf, http://sourceforge.net/projects/iperf/, accessed in 15th January 2012.

[137] WiMAX Forum NWG, "WiMAX Forum Network Architecture: Architecture Tenets, Reference Model and Reference Points, Base Specification", *WMF-T32-001-R016v01*, Release 1.6, Version 0.1, November 2010.

[138] Kamran Etemad, "Overview of Mobile WiMAX Technology and Evolution", in *IEEE Communications Magazine, Volume 46, Issue 10,* October 2008, pp. 31 – 40, ISSN: 0163-6804.

[139] E. Guainella, E. Borcoci, M. Katz, P. Neves, M. Curado, F. Andreotti, Enrico Angori, "WiMAX Extensions to Isolated Research Data Networks: The WEIRD System", Chapter 17, Kwang-Cheng Chen and J. Roberto B. de Marca (Eds.), *Mobile WiMAX*, Wiley, February 2008, pp. 329 – 352, ISBN: 978-0-470-51941-7.

[140] E. Angori, E. Borcoci, S. Mignanti, C. Nardini, G. Landi, N. Ciulli, G. Sergio, P. Neves, "Extending WiMAX Technology to Support End to End QoS Guarantees", *1st WEIRD Workshop on WiMAX, Wireless*

and Mobility (WWW), collocated with 5th International Conference on Wired/Wireless Internet Communications (WWIC), Coimbra, Portugal, May 2007.

[141] K. Knightson, N. Morita, T. Towle, "NGN Architecture: Generic Principles, Functional Architecture and Implementation", *IEEE Communications Magazine, Volume 43, Issue 10*, October 2005, pp. 49 – 56, ISSN: 0163-6804.

[142] P. Neves, S. Sargento, R. Matos, G. Landi, K. Pentikousis, M. Curado, F. Fontes, "A WiMAX Cross Layer Framework for Next Generation Networks", Chapter 11, Marcos D. Katz and Frank H. P. Fitzek (Eds.), *WiMAX Evolution: Emerging Technologies and Applications*, Wiley, January 2009, pp. 199 – 225, ISBN: 978-0-470-69680-4.

[143] P. Neves, S. Sargento, K. Pentikousis, F. Fontes, "WiMAX Cross-Layer System for Next Generation Heterogeneous Environments", Chapter 18, M. Upena D. Dalal and Y. P. Kosta (Eds.), *WiMAX New Developments*, In-Tech, December 2009, pp. 357 – 376, ISBN: 978-953-7619-53-4.

[144] R. Matos, P. Neves, S. Sargento, "Evaluating WiMAX QoS Performance in a Real Testbed", *7th Conference on Telecommunications (ConfTele)*, Santa Maria da Feira, Portugal, May 2009., pp. 315 – 321, ISBN: 978-972-98368-8-6.

[145] G. Martufi, M. Katz, P. Neves, M. Curado, M. Castrucci, P. Simões, E. Piri, K. Pentikousis, "Extending WiMAX to New Scenarios: Key Results on System Architecture and Testbeds of the WEIRD Project", *2nd European Symposium on Mobile Media Delivery (EUMOB)*, Oulu, Finland, July 2008, ISBN: 978-963-9799-25-7.

[146] K. Pentikousis, M. Curado, P. Neves, M. Katz, "Establishing the First European Research WiMAX Testbed", *ERCIM News – Mathematics for Everyday Life*, *nº 73*, pp. 51 – 52, April 2008, ISSN: 0926-4981.

[147] F. Andreotti, G. Landi, S. Mignanti, G. Tamea, P. Neves, M. Spada, K. Pentikousis, "WEIRD Testbeds with Fixed and Mobile WiMAX Technology for User Applications, Telemedicine and Monitoring of Impervious Areas", *4th International Conference on Testbeds and Research Infrastructures for the Development of Networks & Communities (TRIDENTCOM)*, Innsbruck, Austria, March 2008, ISBN: 978-963-9799-24-0.

[148] B. Sousa, P. Neves, M. Curado, S. Sargento, F. Fontes, F. Boavida, "The Cost of Using IEEE 802.16 Dynamic Channel Configuration", *IEEE International Conference on Communications (ICC)*, Beijing, China, May 2008, pp. 383 – 390, ISBN: 978-1-4244-2075-9.

[149] M. Almeida, P. Neves, D. Corujo, S. Sargento, "Improving the Experience of Real Time Services in WiMAX Networks", *6th Conference on Telecommunications (ConfTele)*, Peniche, Portugal, May 2007.

[150] P. Neves, S. Sargento, R. Aguiar, F. Fontes, "Design and Experimental Evaluation of QoS and Mobility Support over Integrated 802.16 MANs and 802.11 LANs", *IEEE Vehicular Technology Magazine, Volume 3, Issue 4*, pp. 39-47, December 2008, ISSN: 1556-6072.

[151] P. Calhoun, J. Loughney, E. Guttman, G. Zorn, J. Arkko, “Diameter Base Protocol”, *IETF RFC 3588*, September 2008.

[152] M. Handley, V. Jacobson, “SDP: Session Description Protocol”, *IETF RFC 2327*, April 1998.

[153] P. Neves, T. Nissila, T. Pereira, H. Ilkka, J. Monteiro, K. Pentikousis, S. Sargento, F. Fontes, “A Vendor-Independent Resource Control Framework for WiMAX”, *13th IEEE Symposium on Computers and Communications (ISCC*), Marrakech, Morocco, July 2008, pp. 899 – 906, ISBN: 978-1-4244-2702-4.

[154] M. Curado et al., “Final Implementation”, *Deliverable D3.2, IST-034622-IP WEIRD*, March 2008.

[155] R. Spada et al., “Testbed and Trials Report”, *Deliverable D5.2, IST-034622-IP WEIRD*, May 2008.

[156] T. Bohnert, M. Castrucci, N. Ciulli, G. Landi, P. Neves, P. Simões, “QoS Management and Control for an All-IP WiMAX Network Architecture: Design, Implementation and Evaluation”, *International Journal of Mobile Information Systems, Volume 4, Issue 4*, pp. 253 – 271, January 2009, ISSN: 1574-017.

[157] J. Franks, P. Hallam-Baker, J. Hostetler, S. Lawrence, P. Leach, A. Luotonen, L. Stewart, “HTTP Authentication: Basic and Digest Access Authentication”, *IETF RFC 2617*, June 1999.

[158] D. Sun, P. McCann, H. Tschofenig, T. Tsou, A. Doria, G. Zorn, “Diameter Quality of Service Application”, *IETF RFC 5866*, May 2010.

[159] R. Fielding, J. Gettys, J. Mogul, H. Frystyk, L. Masinter, P. Leach, T. Berners-Lee, “Hypertext Transfer Protocol – HTTP/1.1”, *IETF RFC 2616*, June 1999.

[160] J. Postel, J. Reynols, “Telnet Protocol Specification”, *IETF RFC 854*, May 1983.

[161] P. Neves, S. Sargento, F. Fontes, T. Bohnert, “Quality of Service Differentiation in WiMAX Networks”, Chapter 34, Christos J. Bouras (Ed.), *Trends in Telecommunications Technologies*, In-Tech, March 2010, pp. 753 – 767, ISBN: 978-953-307-072-8.

[162] J. Monteiro, S. Sargento, A. Gomes, F. Fontes, P. Neves, “IEEE 802.16 Packet Scheduling with Traffic Prioritization and Cross-Layer Optimization”, *1st International Conference on Mobile Lightweight Wireless Systems (MOBILIGHT)*, Athens, Greece, May 2009.

[163] P. Neves, S. Sargento, J. Monteiro T. Bohnert, F. Fontes, “Quality of Service Differentiation Support in WiMAX Networks”, *15th IEEE International Conference on Telecommunications (ICT)*, St. Petersburg, Russia, June 2008, pp. 1 – 5, ISBN: 978-1-4244-2035-3.

[164] M. Castrucci, N. Ciulli, A. Ichimescu, G. Landi, I. Marchetti, C. Nardini, P. Neves, “A Framework for Resource Control in WiMAX Network”, *1st Broadband Wireless Access Workshop (BWA), collocated with 1st Next Generation Mobile Applications, Services and Technologies (NGMAST)*, Cardiff, Wales, Great-Britain, September 2007, pp. 316 – 321, ISBN: 978-0-7695-2878-6.

[165] P. Neves, S. Sargento, R. Aguiar, “Design and Experimental Evaluation of QoS and Mobility Support over Integrated 802.16 Metropolitan and Local Area Networks”, *1st WEIRD Workshop on WiMAX,*

Wireless and Mobility (WWW), collocated with 5th International Conference on Wired/Wireless Internet Communications (WWIC), Coimbra, Portugal, May 2007.

[166] IEEE 802.16 WG, "IEEE Standard for Local and Metropolitan Area Networks. Part 16: Air Interface for Fixed Broadband Wireless Access Systems – Amendment 1: Management Information Base", *IEEE Std. 802.16f-2005*, December 2006.

[167] NET-SNMP, http://net-snmp.sourceforge.net/dev/agent/, accessed in 31st August 2011.

[168] ITU-T, "Dual rate speech coder for multimedia communications transmitting at 5.3 and 6.3 Kbps", *ITU-T Rec. G.723.1*, 1996.

[169] K. Pentikousis, J. Pinola, E. Piri, F. Fitzek, "A measurement study of Speex VoIP and H.264/AVC Video over IEEE 802.16d and IEEE 802.11g", *3rd Workshop on MultiMedia Applications over Wireless Networks (MediaWiN)*, Marrakech, Morocco, July 2008, pp. 19 – 24, ISBN: 978-1-4244-2702-4.

[170] K. Pentikousis, J. Pinola, E. Piri, F. Fitzek, "An experimental investigation of VoIP and video streaming over fixed WiMAX", *4th International Workshop on Wireless Network Measurements (WiNMee)*, Berlin, Germany, March 2008, pp. 8, ISBN: 978-963-9799-18-9.

[171] K. Pentikousis, J. Pinola, E. Piri, F. Fitzek, T. Nissilä, I. Harjula, "Empirical evaluation of VoIP aggregation over a fixed WiMAX testbed", *4th International Conference on Testbeds and Research Infrastructures for the Development of Networks and Communities (TRIDENTCOM)*, Innsbruck, Austria, March 2008, ISBN: 978-963-9799-24-0.

[172] G. Martufi, M. Katz, P. Neves, M. Curado, M. Castrucci, P. Simoes, E. Piri, K. Pentikousis, "Extending WiMAX to new scenarios: key results on system architecture and test-beds of the WEIRD project", *2nd European Symposium on Mobile Media Delivery (EUMOB)*, Oulu, Finland, July 2008, ISBN: 978-963-9799-25-7.

[173] ITU-T, "Advanced Video Coding for Generic Audiovisual Services", *ITU-T Rec. H.264*, 2005.

[174] ISO/IEC, Information technology - Coding of moving pictures and associated audio for digital storage media at up to about 1.5 Mbps - Part 3: Audio. ISO/IEC 11172-3, 1993.

[175] Jugi's Traffic Generator (JTG) – http://www.cs.helsinki.fi/u/jmanner/software/, accessed in 15th January 2012.

[176] Speex: A Free Codec for Free Speech – http://www.speex.org, accessed in 15th January 2012.

[177] PTP daemon (PTPd) – http://ptpd.sourceforge.net/ , accessed in 15th January 2012.

[178] S. Sargento, P. Neves, R. Matos, G. Landi, M. Curado, B. Sousa, K. Pentikousis, "Mobility Management Architecture for WiMAX Networks", Chapter 6, Ramjee Prasad e Fernando J. Velez (Eds.), *WiMAX Networks: Techno-Economic Vision and Challenges*, Springer, June 2010, pp. 251 – 287, ISBN: 978-90-481-8751-5.

[179] L. Cordeiro, M. Curado, P. Neves, S. Sargento, X. Fu, "Media Independent Handover Network Signaling Layer Protocol (MIH-NSLP)", *IETF Internet-Draft draft-cordeiro-nsis-mih-nslp*, February 2008.

[180] P. Neves, R. Matos, B. Sousa, G. Landi, S. Sargento, K. Pentikousis, M. Curado, E. Piri, "Mobility Architecture for NGN WiMAX: Specification and Implementation", *10th IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, Kos, Greece, June 2009, pp. 1 – 10, ISBN: 978-1-4244-4440-3.

[181] R. Matos, B. Sousa, P. Neves, S. Sargento, M. Curado, "Advanced Mobility in Broadband Wireless Access Scenarios", *5th IEEE International Conference on Wireless and Mobile Computing, Networking and Communications (WiMOB)*, Marrakech, Morocco, October 2009, pp. 214 – 220, ISBN: 978-0-7695-3841-9.

[182] University of Coimbra Faculty of Sciences and Technology, http://www.uc.pt/en/fctuc, accessed in 15th January 2012.

[183] Nextworks, http://www.nextworks.it/, acessed in 15th January 2012.

[184] University of Groningen, http://www.rug.nl/, accessed in 15th January 2012.

[185] A. Gomes et al., "Handover Reference Scenarios, Requirements Specifications and Performance Metrics", *Deliverable D2.1, IST-216006 HURRICANE*, July 2008.

[186] N. Carapeto, A. Gomes, P. Neves, G. Kormentzas, L. Sarakis, "HURRICANE Handover Scenarios, Metrics and Testbeds", *Proc. International Conference on Telecommunications and Multimedia (TEMU)*, Ierapetra, Crete, Greece, July 2008.

[187] S. Gunaratne, J. Rodriguez, G. Kormentzas, L. Sarakis, N. Carapeto, P. Neves, A. Gomes, D. Vassis, "HURRICANE: 4G Vision with Seamless Mobility, Service Continuity and Network Interoperability in Mind", *International Conference on Telecommunications and Multimedia (TEMU)*, Ierapetra, Crete, Greece, July 2008.

[188] P. Neves, J. Soares, S. Sargento, "Media Independent Handovers: LAN, MAN and WAN Scenarios", *5th Broadband Wireless Access Workshop (BWA), collocated with IEEE Global Communications Conference (GLOBECOM)*, Honolulu, Hawaii, U.S.A., December 2009, pp. 1 – 6, ISBN: 978-1-4244-5626-0.

[189] P. Neves, M. Melo, S. Sargento, K. Pentikousis, F. Fontes, "Enhanced Media Independent Handover Framework", *69th IEEE Vehicular Technology Conference (VTC2009-Spring)*, Barcelona, Spain, April 2009, pp. 1 – 5, ISBN: 978-1-4244-2517-4.

[190] G. Lampropoulos, P. Neves, J. Lauterjung, A. Gomes, G. Kormentzas, H. Marques, L. Sarakis, C. Skianis, "Specification of Optimized Handover Operations among Cooperative Networking Environments", *ICT Mobile Summit 2009*, Santander, Spain, June 2009, ISBN: 978-1-905824-12-0.

[191] P. Neves, G. Lampropoulos, C. Skianis, L. Sarakis, G. Kormentzas, "Managing Link Layer Resources for Media Independent Handover", *World Intellectual Property Organization (WIPO) submitted patent*, July 2010.

[192] H. Marques et al., "Specification and Design of Optimized Handover Operations", *Deliverable D3.1, IST-216006 HURRICANE*, December 2008.

[193] H. Marques et al., "Design of Optimized Handover Operations for Heterogeneous Wireless Systems", *Deliverable D3.2, IST-216006 HURRICANE*, June 2009.

[194] G. Lampropoulos, C. Skianis, P. Neves, "Optimized Fusion of Heterogeneous Wireless Networks Based on Media Independent Handover Operations", *IEEE Wireless Communications Magazine, Volume 17, Issue 4*, pp. 78 – 87, August 2010, ISSN: 1536-1284.

[195] S. Battista et al., "Implementation of Handover-enabling Modules for Mobile Terminals", *Deliverable D4.1, IST-216006 HURRICANE*, December 2009.

[196] P. Pires et al., "Implementation of Handover Enabling Modules for Network Nodes", *Deliverable D4.2, IST-216006 HURRICANE*, December 2009.

[197] R. Silva, P. Carvalho, P. Sousa, P. Neves, "Enabling Heterogeneous Mobility in Android Devices", *ACM Springer Mobile Networks and Applications (MONET) Journal, Special Issue on Mobile Networks and Management*, Volume 16, Number 4, Springer, August 2011, pp. 518 – 528, ISSN: 1383-469.

[198] R. Silva, P. Carvalho, P. Sousa, P. Neves, "Heterogeneous Mobility in Next Generation Devices: An Android-based Case Study", *6th International ICST Conference on Mobile Multimedia Communications (MobiMedia)*, Lisbon, Portugal, September 2010.

[199] N. Capela, J. Soares, P. Neves, S. Sargento, "An Experimental Testbed of Optimized Inter-Technology Handovers", *11th Conferência sobre Redes de Computadores (CRC)*, Coimbra, Portugal, November 2011.

[200] T. Cardoso, P. Neves, M. Ricardo, S. Sargento, "Media Independent Handover Management in Heterogeneous Access Networks – An Empirical Evaluation", *73rd IEEE Vehicular Technology Conference (VTC2011-Spring)*, Budapest, Hungary, May 2011.

[201] N. Capela, J. Soares, P. Neves, S. Sargento, "An Architecture for Optimized Inter-Technology Handovers: Experimental Study", *IEEE International Conference on Communications (ICC)*, Kyoto, Japan, June 2011.

[202] L. Sarakis et al., "Intermediate Integration of HURRICANE Handover Framework", *Deliverable D5.1a, IST-216006 HURRICANE*, December 2009.

[203] L. Sarakis et al., "Final Integration of HURRICANE Handover Framework at Testing Sites", *Deliverable D5.1b, IST-216006 HURRICANE*, June 2010.

[204] IEEE 802.11 WG, "IEEE Standard for Local and Metropolitan Area Networks – Specific Requirements – Part II: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: IEEE 802.11 Interworking with External Networks Amendments", *IEEE Std. 802.11u*, February 2011.

[205] National Institute of Standards and Technology, NIST – http://www.nist.gov, accessed in 15th January 2012.

[206] E. Hossain, T. Issariyakul, *Introduction to Network Simulator NS-2*, Springer, October 2008, ISBN: 978-0387717593.

[207] ITAv modified NS-2 NIST add-on http://www.av.it.pt/ssargento/802_21_web/main.html , accessed in 15th January 2012.

[208] Redline Communications WiMAX Base Station AN-100U, http://www.redlinecommunications.com/en/products/redmax-wimax-family/an-100u-base-station, accessed in 15th January 2012.

[209] Cisco Lynksis Wi-Fi Access Point WAP54G, http://www.linksysbycisco.com/EU/en/products/WAP54G?lid=LearnMore, accessed in 15th January 2012.

[210] PT Mobile Operator TMN, http://www.tmn.pt, accessed in 15th January 2012.

[211] H. Schulzrinne, A. Rao, R. Lanphier, "Real Time Streaming Protocol (RTSP)", *IETF RFC 2326*, April 1998.

[212] Darwin Streaming Server, http://dss.macosforge.org/, accessed in 15th January 2012.

[213] H. Schulzrinne, S. Casner, R. Frederick, V, Jacobson, "RTP: A Transport Protocol for Real-Time Applications", *IETF RFC 1889*, January 1996.

[214] Distributed Internet Traffic Generator (D-ITG), http://www.grid.unina.it/software/ITG/, accessed in 15th January 2012.

[215] M. Aramoto, M. Nakamura, S. Sugimoto, N. Takamyia, http://umip.linux-ipv6.org/, accessed in 15th January 2012.

[216] Android Operating System – Open Source Project, http://source.android.com/, accessed in 15th January 2012.

[217] HTC Google Nexus One Android Smartphone, http://www.htc.com/us/support/nexus-one-google/tech-specs/, accessed in 15th January 2012.

[218] P. Neves, "Mechanism to Optimize Mobility Processes in Heterogeneous Access Networks", *World Intellectual Property Organization (WIPO) submitted patent*, July 2010.

[219] P. Neves, J. Soares, S. Sargento, "Dynamic Media Independent Information Server", 15th IEEE Symposium on Computers and Communications (ISCC), Riccione, Italy, June 2010.

[220] P. Neves, J. Soares, S. Sargento, H. Pires, F. Fontes, "Context-aware Media Independent Information Server for Optimized Seamless Handover Procedures", The *International Journal of Computer and Telecommunications Networking, Computer Networks, Special Issue on Network Convergence*, Elsevier, Volume 55, Issue 7, May 2011, pp. 1498-1519.

[221] WiMAX Forum, "Industry Research Report", May 2011.

[222] H. Haverinen, J. Salowey, "Extensible Authentication Protocol Method for Global System for Mobile Communications (GSM) Subscriber Identity Modules (EAP-SIM)", *IETF RFC 4186*, January 2006.

[223] MEO, http://www.meo.pt/, accessed in 15th January 2012.

[224] MEO Go, http://www.meo.pt/ver/meogo/, accessed in 15th January 2012.

[225] National Center for Scientific Research (NCSR) Demokritos, http://www.demokritos.gr/, accessed in 15th January 2012.

[226] University of Aegean, http://www3.aegean.gr/aegean/en/intro_en.htm, accessed in 15th January 2012.

[227] Secretary of State Assistant for Entrepreneurship, Competitiveness and Innovation visit to PTIN, http://www.ptinovacao.pt/#/news/?ID=505 , October 2011, accessed in 15th January 2012.

[228] Open Idea International NGIN Users Group, http://www.openidea.pt/eventos/usersgroup2011/, October 2011, accessed in 15th January 2012.

[229] Wireless Broadband Alliance, http://www.wballiance.com/events/events-archive.html, November 2011, accessed in 15th January 2012.